OPTIMAL ALLOCATION OF WATER BASED ON ECONOMIC AND ENVIRONMENTAL CRITERIA: CASES FROM BANGLADESH AND INDONESIA

by

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A dissertation submitted in partial fulfillment of the requirements for the
Degree of Doctor of Philosophy in
Water Engineering and Management

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December 2011

Acknowledgement

I start in the name of Allah (God), the Most Merciful, the Most Beneficial. All my praises be to Him, who has seen me through this work.

I owe deepest gratitude to a number of personalities who lent a hand to me in one way or the other through the tough times of making this research work possible. First, my deepest gratitude is to Dr. Mukand S. Babel. It's an honor for me to have Dr. Babel as my supervisor. He made available his support in this work in a number of ways, from questioning the ideas to converting them into real application. His supervision, systematical thoughts gave me leverage to conduct this research.

I am truly fortunate to have Dr. Sylvain R. Perret as my co-supervisor. My sincere gratitude to him for helping me in several ways to explore through the maze of research at my own, and at the same time provided support and guidance.

I am grateful to the examination committee members Dr. Roberto S. Clemente and Dr. Vilas Nitivatananon for their insightful comments and constructive criticisms that helped me improving the research work.

I am grateful to Professor Bart Schultz from UNESCO-IHE Institute for Water Education for his timely and constructive incisive comments as the external examiner that has improved the dissertation considerably.

I gratefully acknowledge the support and help from the officers and staff of BWDB and IWM in collecting data and information for the research on The Teesta Basin, Bangladesh and support from UNPAR team and PJT-I officials for the work on Konto Basin, Indonesia. I also acknowledge the help and support from many of my friends, relatives and from a two local NGOs while conducting the primary survey at the Teesta site, a very rural environment.

I am also indebted to the whole WEM family, importantly Khun Pajee (Tuk), for all administrative support she provided during these years.

Most importantly, none of this would have been possible without the love, patience and prayer of my parents, wife and my little son, Safwan.

Finally, I appreciate the financial support from the Norwegian Ministry of Foreign Affairs and the grant of study leave from my employer CUET, Chittagong, Bangladesh for completion of this study and research work.

Abstract

The manipulation and alteration of river flow generate significant benefits as well as impact upon ecosystem integrity with loss of ecosystem goods and services, including riparian livelihoods. Poor communities in developing countries are particularly at stake as their lives largely and directly depend on river flows through fishing, navigation and farming activities. Such water-uses bear significant social and economic value, but are often poorly accounted. Ensuring environmental flow (EF) can act positively in preserving these values; nevertheless it results in more competition among water users. Hence, economically efficient yet socially justifiable and environmentally sound water allocation at a river basin scale is an issue of global importance. Tradeoff is obvious in the process but question arises as to what extent the competing water demands can compromisingly be satisfied. In this regard, the research develops a methodology to allocate water optimally between competing sectors including the environment in a river basin scale considering the marginal benefit that each water-use generates.

The dissertation comprises two interlaced topics, successively, i.e. (1) estimating total and marginal benefit functions for the off- and in-stream water uses in a river basin and (2) setting up a model that can allocate water optimally among the competing uses. Off-stream water-use is mainly consumptive use of river water (e.g. for irrigation) that subsequently changes the natural flow regime. In-stream water use refers to use that occurs directly onto the water course (e.g. fisheries, navigation). Environmental flow requirements are estimated and considered as constraints in the optimization model. The model is applied to Teesta River, Bangladesh, and Konto River Basin in Indonesia.

The Teesta flow is modified through an irrigation barrage inside Bangladesh since 1990. Water uses in the Teesta are irrigation, instream fishery and navigation. Konto has a reservoir at the upstream since 1970. A series of three hydropower plants are fed from the reservoir and all the plants use the same water. The water is then sent to an irrigation project. Municipal and industrial uses as well as reservoir recreation and fishery also generate benefits.

Residual imputation method and yield response to water stress form the basis for establishing the benefit functions for irrigation water use. Income variation of the beneficiaries with the variation of river flow within a year forms benefit functions for instream fishery and navigation. Total benefit for irrigation, fishery and navigation are developed as a quadratic relation with river flow that results in a downward slopping linear marginal benefit function. Marginal benefit for hydropower water use is considered constant slope, whereas a hyperbolic tangent function is developed for estimating benefit for reservoir recreation and fishery. Benefit functions are used as input to the optimization model ‘Aquarius’. Alternative scenarios are analyzed and tradeoff between benefit maximization and environmental protection is evaluated for the Teesta and Konto River Basin. Current water management practice in both the basins is found generating the maximum benefit; however, EF is not ensured for any of the studied river. For Teesta site, in existing scenario, irrigation benefit and instream benefits are US$ 43.24 million and 0.58 million respectively when only direct instream uses are considered; whereas ensuring EF results in a benefit reduction of US$ 9.25 million. In case of Konto, overall basin benefits are US$ 16.28 and 15.21 million without and with consideration of EF respectively; however, benefits from instream flow have not been measured in this case.

Although the measured instream benefits from direct uses are much lower than offstream benefits in particular for the case study sites, instream flow is critically important for the socio-economy of the local people. Even satisfying the lowest level of EF results in higher level of income for the poor who have flow-based livelihood; this is particularly marked for the Teesta study site. Although non-use benefits and long term environmental benefits of instream flow would change the optimization model outcomes, they have not been considered. Overall benefit can only be increased if there is augmentation of flow and improvement of irrigation efficiency.

This study can be considered as a pioneering work in valuing the marginal benefit of instream flow and incorporating those benefits into a hydro-economic model. The study also provides in-depth insight into the tradeoff between benefit maximization and environmental protection through provisioning different levels of EF in rivers.

Publications from the Dissertation

A. Refereed international journal articles:

1. Mullick, M. R. A., Babel, M. S. & Perret S. R. 2010. Discharge-based economic valuation of irrigation water: evidence from the Teesta River, Bangladesh. *Irrigation and Drainage*, 60 (4), 481 – 492.
2. Mullick, M. R. A., Babel, M. S. & Perret, S. R. 2011. Optimal water allocation based on marginal benefits from selected uses in the Teesta River, Bangladesh. Submitted to *Water Policy* (Under review).
3. Mullick, M. R. A., Perret S. R. & Babel, M. S. 2011. Marginal benefit functions for instream water direct uses – a case of Teesta River, Bangladesh. To be submitted to *International Journal of Water Resources Development*.
4. Babel, M. S.; Mullick, M. R. A.; Yudianto, D.; Prasad, K. C.; Perret, S. R., Wahid, S. M. and Triweko, R. W. 2011. Drops cascading and successive value addition to water of Konto River, Indonesia: optimal system operation considering environmental sustainability. To be submitted to *Journal of Hydro-environment Research*.

B. Book Chapters

1. Mullick, M. R. A., Babel, M. S. & Perret, S. R. 2009. Managing the competing water demands from offstream & instream users – a conceptual framework. In Blöschl, G., Van De Giesen, N., Muralidharan, D., Ren, L., Seyler, F., Sharma, U., & Vrba, J. (eds.) (2009). *Improving integrated surface and groundwater resources management in a vulnerable and changing world.* IAHS publication no. 330, pp 327 – 333. ISBN 978-1-907161-01-8.

C. Papers in refereed conference/congress/symposium/forum proceedings:

1. Mullick, M. R. A., Babel, M. S. & Perret, S. R. 2010. Hydro-economic modeling for optimal water allocation among in- and off-stream uses in the Teesta River, Bangladesh. In the *Proceedings of the 5th Conference of Asia Pacific Association of Hydrology and Water Resources*, Hanoi, Vietnam, 8 – 10 November 2010. pp. 329 – 339.
2. Mullick, M. R. A., Babel, M. S. & Perret, S. R. 2010. Flow characteristics and environmental flow requirements for the Teesta River, Bangladesh. In the *Proceedings of International Conference on Environmental Aspects of Bangladesh*, University of Kitakyushu, Japan, September 4, 2010. pp.159 – 162.

D. Papers in workshops/Seminars

1. Mullick, M. R. A., Babel, M. S. & Perret, S. R. 2010. Incorporating discharge-based marginal values of in- and off-stream water uses in optimal water allocation – a case study from Bangladesh. Presented in the *Workshop on Cooperation on the Ganges: Barriers, Myths, and Opportunities* held on 13 – 14 November 2010 at the National University of Singapore, Singapore
2. Mullick, M. R. A. and Babel, M. S. 2011. Water resources development in Konto Basin, Indonesia: is that environmentally sound? Paper presented *4th International Joint Student Seminar* on Civil Infrastructures. 1-2 August 2011, Bangkok, Thailand.

E. Abstracts/Presentations of paper

1. Mullick, M. R. A., Perret, S. R. & Babel, M. S. 2009. Instream water use – how much value does it carry? Presented in the 12th River*symposium*, Brisbane, Australia, 21 – 24 September 2009.

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Table of Contents

List of Figures

List of Tables

List of Abbreviations

AC/TC	Average Cost/ Total Cost
ANOVA	Analysis of Variance
BBM	Building Block Methodology
BBS	Bangladesh Bureau of Statistics
BFRSS	Bangladesh Fisheries Resources Survey System
BIWTA	Bangladesh Inland Water Transport Authority
BWDB	Bangladesh Water Development Board
CAS	Catch Assessment Survey
CINI	Change In Net Income
CS	Consumer Surplus
CVM	Contingent Valuation Method
DoF	Department of Fisheries
DRIFT	Downstream Response to Imposed Flow Transformation
EF	Environmental Flow
EFA	Environmental Flow Assessment
FAO	Food And Agriculture Organization
FDC	Flow Duration Curve
GDP	Gross Domestic Product
GWP	Global Water Partnership
HEM	Hydro-Economic Model
IDR	Indonesian Rupiah
IFIM	Instream Flow Incremental Methodology
IHA	Indicator of Hydrologic Alteration
IWM	Institute of Water Modeling
IWRM	Integrated Water Resources Management
MAF	Mean Annual Flow
MDG	Millennium Development Goal
MEA	Millennium Ecosystem Assessment
PHABSIM	Physical Habitat Simulation Model
PJT-I	*Perum Jasa Tirta* (public company) - I
PS	Producer Surplus
RIM	Residual Imputation Method
RVA	Range of Variability Approach
TB/MB	Total Benefit/Marginal Benefit
TC	Total Cost
TCM	Travel Cost Method
TEV	Total Economic Value
TIP	Teesta Irrigation Project
Tk	Taka (Bangladesh National Currency)
UNESCAP	United Nations Economic & Social Commission for Asia & the Pacific
WCD	World Commission on Dam
WTA	Willingness To Accept compensation
WTP	Willingness To Pay
WUA	Wetted Usable Area

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PART-I

Chapter 1: Introduction
Chapter 2: Review of literature
Chapter 3: Research approach and methodology

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1 INTRODUCTION

1.1 Background

River basins are cradles of many of the ancient civilizations on the earth where humanity is endowed with numerous social and economic services that flowing water provides. The seasonal flow patterns of rivers decide agricultural practices, replenish nutrients in the soil, support fisheries that feed societies, provide transportation which is the cheapest and the only mode of haulage in several places, supply power and basic water needs for daily life and form the overall cultures and religions in a region. Such interdependencies between lives and rivers are more pronounced in developing regions yet currently that relationships are at peril largely owing to over exploitation of the rivers.

At present, demands and uses of freshwater outstrip the population and urbanization growth and industrial development. In the last century, global population was quadrupled whereas irrigated agricultural land and fresh water withdrawal was increased by six and eight times respectively (Gleick, 1998). Postel et al. (1996) estimated an appropriation of 54% of earth's available run-off from rivers for off-stream human uses and forecasted that of 70% by 2025 for sustaining the current pace of development. Currently, the world has more than 800,000 dams on its rivers (Rosenberg et al., 2000). Notwithstanding these massive appropriation and alteration of the natural flow, water scarcity both in quantity and quality is a major development challenge in several parts of the world. Irrigation water demand is under a real threat in developing region where the economy largely depends on agriculture. Irrigation is by far the largest water user with in general poor use efficiency and low application of modern technologies in much of the world. An assessment by Schultz et al. (2005) mention that to meet the increased food demand irrigated arable land will reach to 50% from 18% with improved water management intervention such as improved irrigation efficiency, drainage system, institutional reform etc. On the other hand, Falkenmark (2004) shows that water requirement to meet only the irrigation demand by 2050 will be seven times higher than the current demand. In any case, the key question is how much of the natural flow can be diverted for consumptive uses when several economic, technical and more importantly the environmental limits exist over the freshwater supply and its augmentation.

Today's society is living with the legacy of water management that predominantly focuses to accrue benefits mostly through offstream uses meaning that water is abstracted from river: namely, irrigated agriculture, assured water supply for domestic and industrial uses, flood control etc. Such basin development practices are frequently observed in developed countries (WCD, 2000) and increasingly being sought in developing regions aiming to meet the United Nation's goals for human development and poverty eradication (MDGs) (King and McCartney, 2007). However, currently practiced water management in a basin focusing more to offstream uses through alteration of flow regime often ignores the key element of sustainable development – environmental and informal use interests (Kashaigili et al., 2005; Richter et al., 2006). The alteration of natural flow from several hydraulic structures in the rivers including injudicious exploitation of ground water already have resulted an alarming degraded condition of the usable water bodies and associated ecosystem in several places on the earth (Rosenberg et al., 2000). Flow alteration changes the dynamic movement of water and sediment that exist in free flowing rivers (Poff et al., 1997) and ultimately jeopardizes the ecosystem integrity (Naiman et al., 1995; Sparks, 1995; Lundqvist, 1998; Ward et al., 1999).

Losses in ecosystem integrity and degradations of rivers' health critically affect the provision of river-based numerous goods and services on which society depends on myriad ways (Naiman et al., 2002). The ecological services provided by inland water ecosystems are estimated at about US$6 trillion per year (Postel and Richter, 2003). Significance of the ecosystem services has also been emphasized in international forums. Agenda 21 recognizes this issue of ensuring water supply for societal need while preserving the functions of ecosystem. The Millennium Ecosystem Assessment (MEA) identifies,

> *"……any progress achieved in addressing the Millennium Development Goals (MDGs) of poverty and hunger eradication, improved health and environmental sustainability is unlikely to be sustained if most of the ecosystem services on which humanity relies continue to be degraded" – Millennium Ecosystem Assessment (2005).*

Steps aiming to responding the environmental and ecosystem degradation widely focus on ensuring environmental flows (EFs) in rivers (Naiman et al., 2002; Postel and Richter, 2003; Arthington et al., 2006) mostly through environmental impact assessment for the new projects. The concept of EF in water resources management recommends the provision of certain amount of flow in rivers to maintain the natural flow regime and the aquatic ecosystem integrity. Using EF, water managers at present tries to establish a limit up to which a river can be altered from its natural state while maintaining the ecosystem integrity to a certain predefined level or allowing an accepted level of degradation (Tharme, 2003). The objective of EF allocation also considers the social and economic needs along with the environmental requirements at the design phase of any water resources development project.

However, the attendant need to meet the environmental water requirements often leads to competition among the water using sectors. Allocating a part of the flow for nature is frequently observed contentious with offstream demands of irrigation, domestic and industrial uses in several places (Hollinshead and Lund, 2006). Poff et al. (2003) pointed out few of such conflicts, namely (i) Klamath basin of Oregon and California (USA) where the conflict was raised between irrigation and fishery, (ii) in the Apalachicola-Chattahoochee-Flint River basin (USA) where conflicting demands raise from the growth of metropolitan Atlanta, agricultural irrigation, and the Apalachicola Bay oyster fishery, (iii) in the Rangitata River basin, New Zealand where water allocation problem was noted for the requirement of dairy industries and for the ecology, (iv) conflicts between water requirements for irrigation and environment along the Lower Balonne River system in Australia. Smakhtin et al. (2004) estimated the global environmental water scarcity and found that about 1.4 billion people are living in river basins where current water uses are in conflict with environmental water demands; they also mentioned that the Ganges river basin would fall into such conflict if environmental water requirements are satisfied.

Advances in understanding and recognition of EF and progresses in developing EF assessment methodologies are considerable. However, developing EF policies is still in its infancy especially in developing countries (Tharme, 2003) and successful implementation of those policies remains a challenge for all nations (Gleick et al., 2006). Yet recent researches (e.g. Moore, 2004; Scatena, 2004; Gleick et al., 2006) argue that recognition of the importance of flow to local livelihood and better understanding of benefits and costs involved with instream water provision underpin the successful implementation of EF. Realizing the economic value of instream water uses such as navigation, wetlands, fisheries, and recreation is the fundamental to institute instream flow and that can offer an appropriate balance between environmental needs and off-stream human consumption. Satisfying all water-users including environment often demands reallocation of water between sectors; however, such actions can be treated myopic, unless potential repercussion towards the socioeconomic benefits and costs are well documented and addressed.

Sustenance of the economy, keeping pace of the national development and reducing the hunger gap in one hand and an untapped supply of in-stream water goods and services through protecting the increasingly degraded environment along with safeguarding the livelihoods of the rural mostly the riparian poor on the other hand, water resources management is currently facing a critical challenge (King and McCartney, 2007; United Nations, 2007). Hence, in this changing world with rapidly growing human populations, wise management of freshwater both for human and nature is an issue of global importance (Gleick, 2002; Vörösmarty, 2002).

In this regard, allocating water among the competing users is the central to the management of water resources. Richter et al. (2006) highlighted considerable controversy surrounding inherent trade-off required to ensure instream flow; however, the issue can be addressed through the economic value of water uses because the rationale of inter-sectoral distribution of the resource is in general economic (Molle et al., 2007). Economic valuation also plays role in equitable resource allocation, managing conflicts and for informed decision-making (Farber et al., 2002; De Groot et al., 2006). Nevertheless, there is a general lack of comprehensive information on economic value of all offstream and instream water uses at basin scales and incorporating those values effectively in water allocation decisions.

1.2 Problem statement

Allocating water efficiently to all water uses including environmental use is a critical issue owing to challenges of valuing water uses in particular the instream uses. To date, there have been a number of researches that have tried to value the instream water uses and services rendered to society and associated ecosystem. Some examples include Duffield et al. (1994), Douglas and Taylor (1998), Xu et al. (2003), Webber and Berrens (2006), Ojeda et al. (2008) etc. Majority of these studies estimated the total value (total value averaged over total available resource) particularly for instream water and/or associated ecosystem which is often viewed insufficient because of its failure to provide information in allocating water to its highest use-value on margin.

Total value may provide considerable justification for water investment decision (Young, 1996); however, the marginal value – explicitly indicating the change in total value due to change in resource input – of alternative water uses is the most important parameter in water allocation decision that often concerns trade-off analyses from the management perspective (Gleick et al., 2006; Smakhtin et al., 2006; Moran and Dann, 2008). In this context, an economically efficient water allocation that seeks to equate the marginal values of water among all water demands remains a real challenge for the river basin management.

Moreover, water allocation is often focused on maximization of benefit or minimization of shortage of water. In few cases, a fixed amount of instream water requirement is taken as a constraint which fails to ensure the natural variability of flow as well as it falls short to comprehend benefits accrued from instream flow. Suen and Eheart (2006) and Shiau and Wu (2007) included instream flow in objective function in their multi-objective optimization problem and presented the trade-off scenario of water supply to ensure instream water demand. However, economic benefits with trade-off scenarios are not considered which are extremely important for improved water allocation model and informed decision-making at a river basin scale.

A number of studies carried out on hydro-economic modeling for water allocation considering different allocation criteria such as improvement of basin water use efficiency, economic impacts of policies analyzing water market and water transfer issue, alternative water pricing, analyzing the existing allocation policy etc. Very recently a comprehensive state-of-the-art review on hydro-economic model is given by Harou et al. (2009). In several modeling studies the instream water use benefits are mainly considered as hydropower generation and lake and reservoir recreation. However, it is apparent in many developing countries that the poor's livelihood carries significantly more economic value than recreation. Studies estimating the marginal value garnered from the flowing water in the river used by the riparian poor and considering that benefits into an integrated hydro-economic model are very rare.

1.3 Research questions

The problems of water allocation between offstream and environmental uses are intriguing. First, while the importance of instream water provision is known for decades, basin managers are reluctant in recognizing and adopting the in-stream water requirements especially in developing countries. Second, while the valuation and trade-off techniques had been researched on quite broadly, their implementation in basin scale water resources management had not been encouraging and degradation of ecosystem increased unabated. This leads to the central research question of this study:

- Can we allocate water in economically efficient yet socio-environmentally justifiable manner between offstream and instream sectors including environmental water uses at a river basin scale?
- What would be the consequences to the overall benefits while we consider environmental flow in water allocation process?

1.4 Research objectives

The overall objective of this research is to contribute to better water resources management at river basin level by setting up a model for allocating water optimally among all users considering economic and environmental aspects. To achieve the overall objective, the specific objectives of the study are:

- To set up a mathematical model for optimal water allocation among the water-use sectors using the marginal benefit function for each water-use as the allocation criterion while environmental protection is simultaneously considered;
- To apply the model in two river basins, one from Bangladesh (Teesta river basin) and another from Indonesia (Konto river basin).

The sub-objectives of the study are as follows:

(i) To review the methods for valuation of water in different uses and to develop the marginal benefit functions for the water uses including (direct) uses of instream flow that exist in the study site river basins;

(ii) To review the environmental flow assessment methods and to quantify environmental flow requirements for the case study rivers;

(iii) To set up an optimization model for water allocation among all water-users that simultaneously considers environmental flow demands for the river following the natural flow regime; and

(iv) To elucidate the sectoral and overall benefits from water uses and tradeoff between economic efficiency and ensuring environmental flow at the sectoral and basin level after applying the model for the study basins: namely, the Teesta from Bangladesh and the Konto river basin from Indonesia.

1.5 Scope and limitations of the work

The research covers a developing country perspective where the interests of the subsistence users of river water are often neglected in water resources management and only gross economic development (most of the cases through irrigation) is often focused in policy formulation. Developing countries are in general data poor and provision of environmental flow is not well established. Handling with such issues and challenges the research:

- Assesses instream flow requirement based on hydrological methods (Tennant, Flow Duration Curve and Range of Variability Approach method) and set up the monthly instream flow requirements;
- Estimates total and marginal benefit functions of offstream (e.g. irrigation, domestic, industrial uses) and instream water direct uses (e.g. hydropower, fisheries, navigation, recreation);
- Sets up an optimal water allocation model for water allocation based on the developed marginal benefit functions;
- Applies the model to the study river basins (Teesta from Bangladesh and Konto from Indonesia), verifies the model outputs and estimates the optimal benefit at the (sub)-basin level. Model also runs for several scenarios and depicts the trade-off picture between economic efficiency and environmental protection.

Provision of environmental flow ensures several ecosystem goods and services, which in many cases are difficult to estimate their actual benefit due to lack of research and data. However, the scope of the study is kept limited to consider the major/direct uses of in-stream water. The study does not consider the water quality effect on water uses to estimate their benefits. Analyses at few places are carried out based on several assumptions and using simpler techniques due to paucity of data.

Floodplain activities, mainly the floodplain agriculture and fish culture which is especially important for Bangladesh depends on monsoonal flow and retreat of the river water and highly related to flood events. However present study is focused on water allocation, which is more an important issue for the lean flow period (dry season), hence floodplain activities are not considered in the model.

1.6 Dissertation outline

The dissertation is divided into four parts as described below.

Part I

This part includes three chapters: namely, Chapter 1 Introduction, Chapter 2 Review of literature and Chapter 3 Research approach and methodology. This first chapter introduces the study by presenting the background of the research, the statement of the problem, objectives, scopes and limitations of the research. Chapter 2 reviews water allocation practices with presenting the context of existing theories of water valuation techniques and water-use benefit functions for different traditional and non-tradition off- and in-stream water uses. The chapter also reviews the literature related to environmental flow estimation. Finally the state-of-the-art on hydro-economic modeling works is presented. Chapter 3 describes the research approach and the overall methodological framework of the study.

Part II

This part includes five chapters: namely, Chapter 4 Teesta river: study site in Bangladesh, which describe the study site description, Chapter 5 and 6 respectively Benefit function for offstream water use in Teesta and Benefit functions for instream water uses in Teesta where benefit functions of water uses in the Teesta have been established; Chapter 7 Environmental flow estimation for Teesta and Chapter 8 Optimal water allocation in Teesta where optimal water allocation for the Teesta using commercial software 'Aquarius' is carried out and benefits are estimated. Several scenarios are analyzed and finally tradeoff between economic efficiency and environmental sustainability is examined.

Part III

This part includes three chapters: namely, Chapter 9 Konto river: study site in Indonesia and data collection, which describes the Konto River basin, Indonesia with a brief narrative of water resources development at the site and data collection for the research; Chapter 10 Benefit functions of water uses in Konto where the benefit functions for all the water uses in the Konto river basin are established and Chapter 11 Optimal water allocation in Konto, which provides optimal water allocation for maximization of benefit at the basin level using Aquarius model. Different alternative scenarios are set and run, which in turn shows the sensitivity and tradeoff for alternative water management options.

Part IV

This part contains only one chapter: Chapter 12 Summary, conclusions and recommendations. This chapter concludes the study by providing a detailed discussions and conclusions. A number of recommendations based on analyses and for future research are provided. In addition, findings and contribution of this study are also presented in this chapter.

Finally, a list of all references cited in the dissertation report is presented.

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2 REVIEW OF LITERATURE

2.1 Water allocation in water resources management

Considering a shared resource, rivalry with river water is an age long history which can be grasped looking into the etymology of the words, 'rivalry' and 'river', both originated from the same Latin source '*rivalis'*. However, with the course of time the dimension of the rivalry has been changed; it is no more only between the inhabitants of opposite banks rather between different water using sectors and lastly human versus nature, where efficient water resources management looks into water allocation issue.

> *"The simplest definition of water allocation is the sharing of water among users. A useful working definition would be that water allocation is the combination of actions which enable water users and water uses to take or to receive water for beneficial purposes according to a recognized system of rights and priorities" – as mentioned by UNESCAP (2000).*

Water allocation thus indicates distribution of available water resources to its demanding users subject to hydrological balance and preset management principles such as equity, efficiency, sustainability. Owing to the time-varying characteristics of water availability, acute importance spanning from basic human needs to national economy within a complex web of interaction between climate, hydrology, society, environment, economy and sustainable development, water allocation is a complicated process.

2.1.1 Water allocation criteria

The overall objective of water allocation is to maximize benefit from water related services to the society as a whole. However, this general objective implies some specific aims to be achieved such as social (equity), economic (efficiency) and environmental (soundness) issues and interests as suggested by different donor agencies and management authorities. Nevertheless achieving equity, efficiency and environmental protection at the same time is a daunting challenge and largely depends on acceptability from all the stakeholders where insight into the tradeoff is required. Therefore, water resources management seeks realistic basis and elements for reasonable water allocation towards achieving those objectives to the maximum possible level. Table 2.1 lists the commonly practiced elements/basis of water allocation schemes.

2.1.2 Water allocation within a system approach

Due to the competing and complementary nature of water uses, water allocation often needs a compromise between social and economic preferences while keeping in mind the environmental needs. This complicated phenomenon calls for system modeling for water resources management.

Table 2.1 Commonly practiced bases in water allocation

Basis of water allocation	Brief description
Legal	Water rights and legal framework for water uses in the basin
Institutional	Government and non-government responsibilities and agencies which promote and oversee the beneficial uses of water
Technical	The monitoring, assessment and modeling of water and its behavior, water quality and the environment
Financial/economic	The determination of costs and recognition of benefits that accompany the rights to use water, facilitating the trading of water
As public good	The means for ensuring social, environmental and other objectives for water
Structural and development base	Structural works which supply water and are operated, and the enterprises which use water

Source: UNESCAP, 2000

Both simulation and optimization models are frequently used by water managers in managing the water resources system. Simulation models simulate the system behavior in accordance to predefined allocation and operation rules. Such models give the economic, social and environmental responses for alternative allocation scenarios. However, simulation models can not achieve the optimal outcomes over a specified time period. Optimization models therefore are used to optimize the system performance by allocating water to the users. Nonetheless, in case of water allocation problems, optimization models must be embedded with simulation component to calculate the hydrologic balance. Some sort of integrated simulation-optimization models are used to solve the water allocation problem in case of competition exists over the scarce resource. Assessment of system performance can be well assessed through simulation models whereas optimization models are helpful where enhancement of the system performance is targeted (McKinney et al., 1999). Section 2.4 provides more detail discussion.

2.2 Efficiency in water allocation – insight into value of water

Traditionally water is regarded as ‘free’ resource and the out-of-stream users in general pay a portion of the transportation, treatment and disposal cost of water. Opportunity costs of water uses are often unnoticed and the users pay little attention to use the resource in an efficient manner (Agudelo, 2001). However, efficient water resources management treats water as an economic resource (Briscoe, 1996 cited in Rogers et al., 1998). Considering such economic aspects, water allocation and use often follow the principle of economic efficiency – water should go to its most valued uses; however, in that case the social value of water should not be ignored.

For an example, in the past lot of efforts were put on irrigation sector to increase social benefit; however, it needs to see whether the social marginal value of irrigation water differ from other user groups; otherwise, a reallocation among the users is necessary to maximize the overall social net benefit (Sampath, 1992). In case of an optimal allocation, proper care and attention should go to the marginal values of all the uses including the in-stream ones and particularly the water use by the marginalized poor riparian groups.

Realizing and recognizing value of individual water uses therefore appears most important issue in water resources management. Dublin Statement mentioned –

> *".....past failure to recognize the economic value of water has lead to wasteful and environmentally damaging uses of the resource. Managing water as an economic good is an important way of achieving efficient and equitable use, and of encouraging conservation and protection of water resources." – Principle no. 4, the Dublin Statement.*

Increasing demands as well as various economic and technical limits over supply augmentation often make the water a constraint in economic activity and require meaningful decision in water allocation between competing users including the environment or the river itself. Water managers therefore frequently seek the values and demands of the water in its uses. Economic values in water uses provide insight into the investment decision for waterworks required for water supply, for allocation or more importantly reallocation of the scarce resource among competing sectors, in estimating benefit for improved water quality and for policy formulation (Agudelo, 2001; Young, 2005; Hussain et al., 2007). Economic valuation indeed offers a common metric to evaluation for one use and demand against another and gives insight into equitable resource allocation with necessary trade-off (Loomis, 2000; Griffin, 2006). More importantly, economic analyses of water demand and supply help water professionals in shifting the concept of a discrete volumetric demand to a demand function. Shortcomings of the terms like water requirements or needs are increasingly becoming evident in this regard (Griffin, 2006).

Water allocation that follows an equal marginal value per unit of the resource across all uses is economically the most efficient allocation (Dinar et al, 1997; Agudelo, 2001; Turner et al., 2004; Gleick et al., 2006; Moran and Dann, 2008). Equality in marginal values across the uses indicates no further redistribution is possible to make any sector better off without making another user worse off, which shows a Pareto optimal situation. However, the Pareto optimal theory is based on the underlying assumption that all the demands are competitive. Nevertheless, in reality not all the water demands are competitive or rival; there are complementarities or non-rivalness as well e.g. the instream water uses. To find the Pareto optimal allocation the non-rival and rival demands need a vertical and horizontal addition respectively (Griffin, 2006) (as discussed in section 2.2.3.2) to develop a single demand function when they exist at a certain use-node.

2.2.1 Value, economic value and willingness to pay

The term 'value' indicates an action or object to a user-specified objective or goal (Costanza, 2000). Value covers a wide spectrum in its conceptual meaning. However, the economic value is in focus here. Welfare economics – the science that determines the best possible use of the available resources for human welfare – provides the foundation to the economic concept of value. Nevertheless, such anthropocentric focus does not preclude the interest of the other species which offers the basis for non-use values (Freeman, 1993). The functionality of economic value in deed counts the individual welfare changes where the individuals have their own scale to measure the relative utility of a goods and service usually in a monetary term. In some cases it measures the well being loss due to inadequate or excessive supply of the resources, whether or not market prices exist for the well beings or preferences (Young, 2005; Hussain, 2007).

In the foundation of both anthropocentric and utilitarian notions, economic value conceptualizes the idea of resources scarcity. Economic value of the resources in such a scarcity context implies the willingness to pay (WTP) by the individuals for goods and service provided by the resources or the maximum amount an individual is agreed to forego (willingness to accept compensation [WTA]) in receiving other goods and services to obtain the same level of commodity (Young, 2005). WTP or WTA is therefore the fundamental measures of economic value; however, both of these two measures need not be of equal by principle mainly due to human psychology (Agudelo, 2001). Considering individual WTP (or WTA) for the goods and services as the measuring unit, total economic value of a good to society indicates the aggregated WTP of all individuals' (Young, 1996; Turner et al., 2004).

2.2.2 Demand-supply function, consumer and producer surplus

In a perfectly competitive market, the price of a commodity interprets the expression of WTP at the margin. However, for the non-marketed goods and services, WTP or WTA acts as the theoretical basis to determine the value of a good which is normally referred as the shadow price (Hussain, 2007). The market price is determined from the equilibrium point of supply and demand curves – the point at which the consumer's WTP for the next unit equals the marginal cost of production of that commodity. Consumer's marginal WTP for all previous units purchased exceeds this market price (Agudelo, 2001). A conventional demand-supply curve (Figure 2.1) comprehends this phenomenon in a clear way.

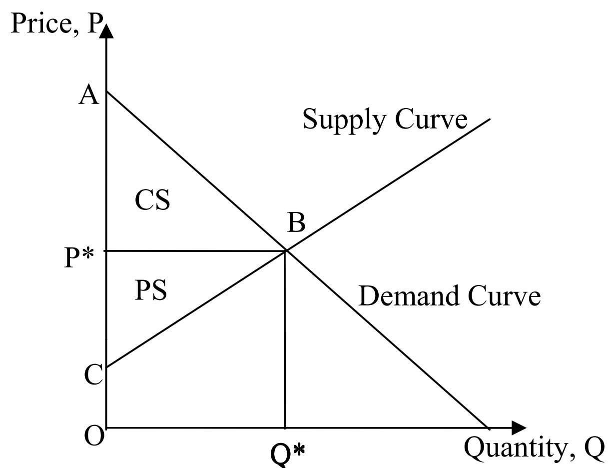

Figure 2.1 Typical demand-supply function

A typical demand-supply function elucidates several terms: total economic value (TEV), average value (AV), total cost (TC), average cost (AC), marginal value (MV), consumer surplus (CS) and producer surplus (PS). A supply function describes the marginal production cost for the producers; on the other hand a demand curve illustrates the marginal benefit that a consumer or a group of consumers can obtain. In other words the demand curve shows the WTP by the consumers for the commodity. Consumers are willing to purchase Q* amount of goods at a price P* where consumers' payment is the area bounded OP*BQ*. Consumers are paying less in compare to what they are willing to pay (area ABQ*O). The difference in the amount of consumers' WTP and what they are actually paying is the consumer surplus (area AP*B). Consumer surplus provides significant conceptual basis for many non-market valuation approach (Saliba and Bush, 1987).

Total economic value equals the total WTP of all individuals i.e. the area ABQ*O. Average value for this case is (area ABQ*O)/Q*. Producers cost is the area bounded by OCBQ*, whereas the consumers are paying the amount bounded by OP*BQ*. The difference between these two amounts is the producer surplus (area BCP*). The sum of producer surplus and consumer surplus provides the basic approximation of the net benefit garnered from the goods and services originating from the resource. Marginal value explicitly indicates the benefit acquired from using one more unit of resource which is measured by the slope of demand curve (dP/dQ) at any point. In a competitive market equilibrium, price P* represents the marginal value for a unit of resource at Q*.

2.2.3 Economic valuation of water as a natural resource

Several researchers argue that economic valuation of natural resources is either impossible or unwise and some are even distrustful of economists' efforts in this regard (Freeman, 1993; Costanza et al., 1997). Moral perspective is an added dispute in this field, which tells that the conservation of natural resources should be from the moral point of view diminishing the economic interests. However, Costanza et al. (1997) were advanced in their statement that both the perspective of economic and moral issues are not mutually exclusive rather they should go in parallel. Costanza (2003) argued for valuation of the ecosystem services that originate from the individual and social purpose to which a society aspire.

Humanity depends on natural capital (natural resources) and associated ecosystem services in myriad ways (Costanza, 2003). Realizing and apposite understanding of the potential value that the natural resources carry is requisite for proficient resource management (De Groot et al., 2006). Along this line economic valuation of natural resources provides insight in finding the trade-off involved in decision making process (Farber et al., 2002).

Several concepts of values and then terminologies are available in literature and being practiced and used in valuation of natural and environmental resources; e.g. De Groot et al. (2002) divided the value of environmental resources into ecological value, socio-cultural value and economic value; Young (2005) mentioned about extrinsic (instrumental) and intrinsic value; Rogers et al. (1998) describes as economic value and intrinsic value; King et al. (2003) and Smith et al. (2006) distinguished the value into use (direct and in-direct) and non-use (existence, bequest and philanthropic) value.

Most often the policy decisions neglect the ecosystem services owing to the inability of those service-values to be fully captured into commercial market (Costanza et al., 1997). However, the value of these services may be as high as infinite when services are treated as life support system. Costanza et al. (1997) advocated considering the marginal value of these services while making a contrast between normal substitutable goods and ecosystem goods in demand-supply function. Howarth and Farber (2002) mentioned the value of ecosystem services as multiplication of services with corresponding shadow prices where its operationalization is constrained by the limitation of non-market valuation methods.

2.2.3.1 Economic value of water

As the most important natural resource, water and in particular the naturally flowing water provides life support system as well as contributes to economic development with numerous goods and services. All these services carry enormous value to the society in different dimensions. Global Water Partnership (GWP) has specified that the full value of water comprises of direct use value, indirect use value, social objective value and intrinsic value (Figure 2.2); where the economic value is specified as the summation of all the values except the latter one. De Groot et al. (2002) put emphasis on ecosystem functions and services in finding the total value of flowing water. They mentioned that the ecological value, socio-cultural value and economic value in together composed of the total value (Figure 2.3). Chowdhury (2005) mentioned about system value which is the aggregated average value that a unit of water generates as it moves through the river system.

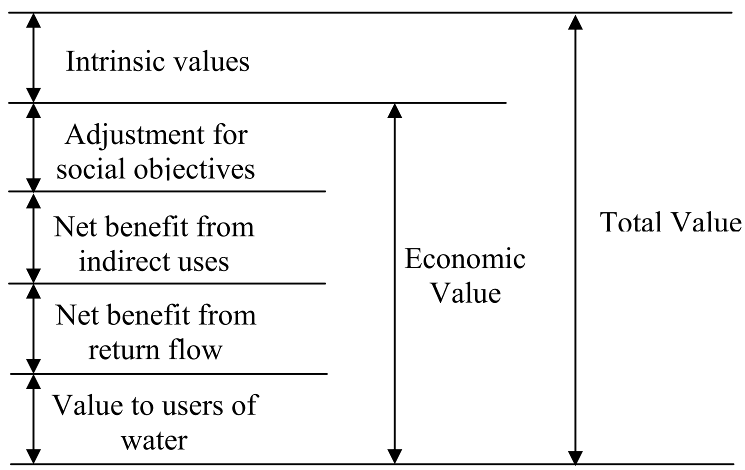

Figure 2.2 Full value of water with its components
Source: Rogers et al., 1998

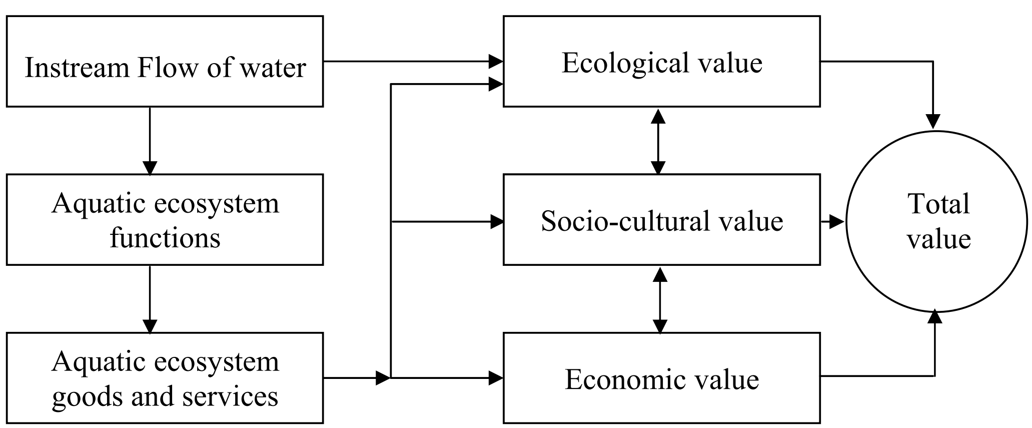

Figure 2.3 Framework in linking instream flow, functions, services and value
Source: De Groot et al., 2002

2.2.3.2 Water value at its use-dimension

Water-use value arises from the direct uses of water by consuming it or its services in any form. However, the use has several dimensions (such as place, time and form of water uses) and considering those dimensions are especially important when comparing the values of water against different uses. For fair comparison, adjustment might be required between uses from other dimensions. Table 2.2 demonstrates different dimensions of water uses. 'Location' specific water use is of more interest for the research, where a water-use is considered as off-stream when water is taken out from the river and after the use the water does not return back to the main course of the river at the point of its previous uptake. Examples include, municipal and industrial uses, agricultural uses. The opposite holds true for instream use case where water is not abstracted for use, examples are fishery, navigation etc.

Table 2.2 Dimensions of water uses

Principal categorization	**Sub-classification**	**Examples of uses**
Location	(i) Off-stream use	Agriculture, Industry, Domestic
	(ii) Instream use	Navigation, Fishery, Hydro-power, Casual uses etc
Economic role	(i) Use as private good	
	- Producers' good	Agriculture, Industry, Hydropower etc.
	- Consumers' good	Domestic
	(ii) Use as public good	Navigation, Pollution abatement etc.
Subtractability	(i) Consumptive use	Agriculture, Industry, Domestic etc.
	(ii) Non-consumptive use	Navigation, Fishery, Hydropower etc.
Realizing total value	(i) Direct use	Agriculture, Industry, Domestic, Navigation, Fishery etc.
	(ii) Indirect use	Recreation, Biodiversity conservation etc.
	(iii) Non-use	Existence (Option value, bequest value), spiritual and cultural value

Source: Based on Agudelo, 2001 & Emerton and Bos, 2004

Water quality is an important characteristic for water uses. Every use of water has its own quality criterion. Changes in quality due to one use restrains some other beneficial use of that water in other places while the value of water changes. Quantity of water use is also a necessary criterion in valuing water since water withdrawal and consumption does not necessarily same across the uses. Water use often faces competition (rival uses) and complementarities (non-rival uses) and that affects to its overall value. Water can be used repeatedly or even simultaneously in different uses such as in-stream uses of hydropower, fishery, navigation etc. In defining the marginal benefit functions for non-rival and rival uses, demand functions need a vertical and horizontal addition respectively to develop a single demand function when they exist at the same use-node (Griffin, 2006). Figure 2.4 demonstrates the horizontal and vertical addition process of the demand function. For simplicity, the demand functions are considered linear.

2.2.4 Water valuation techniques and their applications

Classification of water use based on economic role (as presented in Table 2.2) shows two types of water uses namely: public (non-rival) and private (rival). In general, public-use indicates the use by one individual does not diminish the water availability to other users. Valuation methods differ for public and private uses of water and several methods are in practice to value the water. The available methods for water valuation can broadly be categorized into two: inductive method and deductive method. Inductive techniques/methods – most often applied for public goods valuation – are based on the principle of observation to general relationship (Young, 2005). In contrary the deductive techniques are of most suitable to producers' good valuation. Deductive techniques are based on construction of behavioral and/or empirical model from which the shadow prices are deduced (Young, 2005). Table 2.3 describes the most commonly used water valuation techniques.

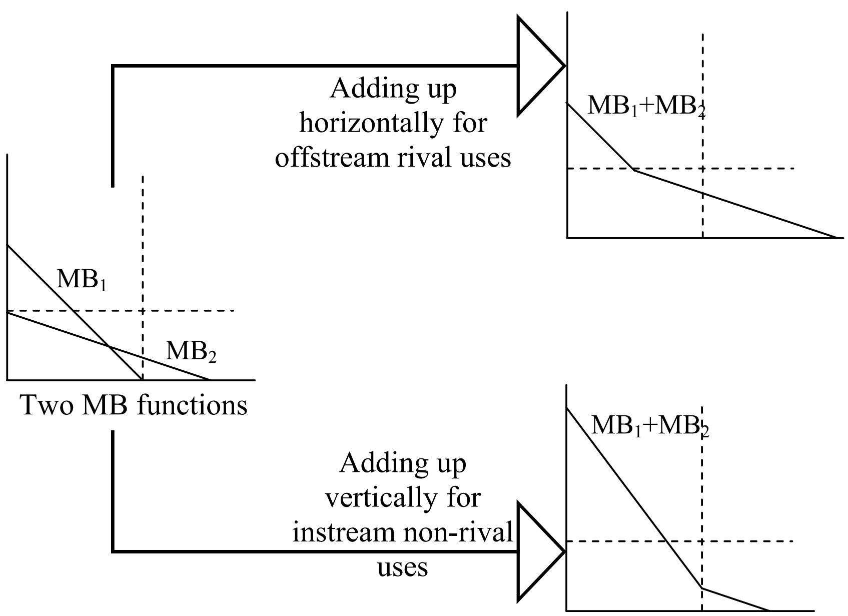

Figure 2.4 Addition of rival and non-rival demand functions
Source: Based on Griffin, 2006

2.2.4.1 Water valuation studies

A number of techniques for measuring the economic value of water uses are available as discussed above. These techniques call for a wedding of economic theory and applied economic practices (Young, 2005). Theoretical development of non-market valuation techniques with application in actual cases for environmental resources are well-developed; however, application of the valuation techniques for water uses as intermediate or producers' goods such as industrial water use, irrigation use, hydroelectric power are found to have received less attention (Young, 1996).

Several studies estimated the value of in-stream water uses focusing mainly the recreational uses applying principally contingent valuation method (CVM) predominantly applied in developed countries; examples include, use of CVM in Cache la Poudre River, Northern Colorado, USA by Daubert and Young (1981); in Montana's Big Hole and Bitterroot Rivers, USA by Duffield et al. (1992); for Colorado River by Booker and Colby (1995); in Idaho and California by Loomis (1998).

Table 2.3 Brief descriptions of economic valuation techniques relating to water resources

Valuation technique	**Brief description of the technique**	**Applicable for valuing water as:**	**Capability to generate MB function**	**Remarks**
1.1 Inductive techniques - Direct market valuation approach				
Producer or consumer demand function	Based on historical water use behavior across variations in real price. Theoretically the technique is sound; however application is challenging (Walker et al., 2000). Three different techniques commonly applied to derive demand function, viz. Production function; Price elasticity and Econometric approach.	Intermediate and final use	Yes	Large body of literature available e.g. Hanemann, 1997 (cited in Lange, 2006)
Water market transactions (rentals and sales)	Trading of water in a competitive market representing the marginal value (MV), practiced in Australia, USA, Chile etc.	Transaction between all sectors.	Yes	Needs institutional support. Competitive markets are not available and transaction prices do not reflect MV.
1.2 Inductive techniques - Indirect market valuation approach				
Revealed preference				
Hedonic price	Based on individual perception and observed data. Value of water is the difference in the price of marketed goods due to water attributes. It needs a freely functioning and efficient property market with perfect information and mobility for individuals. It can capture only part of total value.	Final and intermediate (irrigation) uses	No*	Widely used for recreation and irrigation water valuation. Koundouri and Pashardes (2002) (cited in Lange, 2006) applied this technique in Cyprus to estimate irrigation water value.
Travel cost method (TCM)	Costs of travel (transportation + time) incurred in reaching a recreation site are used as WTP. The method reflects consumer choice behavior and assumes that water is likely to be the only attractive attribute of a site. TCM measures only the use value and is limited to recreational uses.	Final use (direct and indirect uses)	No*	Difficulty in measuring the value of travel time. Can not be employed for non-use value.

Table 2.3 Cont'd

Valuation technique	**Brief description of the technique**	**Applicable for valuing water as:**	**Capability to generate MB function**	**Remarks**
Cost based approach				
Replacement cost	Taking a "shadow Project" where services from water can be replaced by manmade systems. Better to use where benefits cannot be estimated easily.	Waste water treatment plant	No	
Damage cost avoided	The costs that would be incurred in absence of the services. The technique only measures lower bound of WTP.	Flood control structure. Cost in technology to prevent water pollution	No	Hajkowicz and Young (2002) (cited in Lange, 2006) estimated marginal damage cost for increasing salinity in Murray river, Australia
Factor income	Services provide for the enhancement of incomes.			
Benefit transfer	Benefit measured in one context can be transferred and used in other context where suitable comparison studies are available.	Adaptable in principle for private uses and environmental goods	No	
1.3 Inductive techniques - 'Constructed market' valuation approach				
Stated preference				
Contingent valuation method (CVM)	Based on a hypothetical market by direct surveying of a sample of individuals asking individual WTP and aggregation to encompass the relevant population.	Final use, non-use value	Yes	Popular technique for valuing non-market environmental goods.
Conjoint analysis/ contingent ranking	Same concept of CVM; however, individuals are asked to rank the importance of each attribute.	Ecosystem services	Yes	
2. Deductive techniques				
Residual imputation method (RIM)	Budget analysis that seek the return attributable to water after subtracting all non-water expenses assigned by market force.	Intermediate use, does not measure non-use value	No	Suitable when water is a large input e.g. irrigation. Cost of all inputs should be accounted carefully.
Change in net income (CINI)	CINI is a variant of RIM especially applied for multi-product operation.	Intermediate use	Yes	

Table 2.3 Cont'd

Valuation technique	Brief description of the technique	Applicable for valuing water as:	Capability to generate MB function	Remarks
Value added	Static input-output model of production. Based on a sectoral production function rather than isolating only the contribution of the water resource.	Intermediate use (mainly for agriculture and industry).	No	Seriously biased, normally overestimate the value
Alternative cost/ opportunity cost	Benefit from best alternative project is assigned as value to water in a water related project. Some analysts see the technique as a cost-effectiveness analysis	Intermediate (agriculture and industry) and final instream uses e.g. hydropower and transportation	No	Re-circulation of water creates problem in accounting the value
Mathematical programming	Using optimization model to estimate the shadow prices of all constraints including water. Shadow prices give the marginal value of water under the optimal condition.	Intermediate use especially for multi-product, multi-technology cases	Yes	

Note: MB = Marginal Benefit; * According to Griffin (2006) it can be adaptable, but it tests the limits of commonly available data
Source: adopted from Agudelo, 2001; De Groot, 2002; Griffin, 2006; Turner et al., 2004; Young, 1996 and Young, 2005.

Loomis (1998) listed different techniques such as TCM and CVM for non-market valuation of instream flow and mentioned five such case studies from USA. He stated that the dollar value of instream water and its uses can favorably be compared with the traditional out of stream uses.

Douglas and Taylor (1998) applied CVM and TCM method to study the non-market benefit of Trinity River in California. Trinity River has lost its original flow due to Trinity Dam constructed in 1963.

Webber and Berrens (2006) estimated instream recreation value for the Sonoran Desert Canyon and associated instream flow in Southern California through a travel cost analysis. Several studies value in-stream water for endangered and at-risk fish species e.g. Berrens et al. (1996); Loomis (1998); Hickey and Diaz (1999); and a number of studies estimated bequest and existence values e.g. Loomis (1987); Brown and Duffield (1995).

Xu et al. (2003) estimated total economic value of ecosystem services using CVM in China whereas Ojeda et al. (2008) found total economic value of environmental services from in-stream flow in Mexico using CVM.

Studies related to valuation of water for navigational uses are not many. Gibbons (1986) provided a comprehensive treatment of the topic and she mentioned six estimates of short-run average value of water for navigation in the USA.

On the other hand, several studies are found estimating irrigation water value by applying different techniques e.g. econometric valuation from primary (e.g. Turner et al., 2004) and secondary (e.g. Moore, 1999) data, residual imputation method by Speelman et al. (2008), use of hedonic property value by Butsic and Netusil (2007) etc.

Most of these water valuation studies estimated average aggregated value of the resource; however, few of them found only a single-point estimate of marginal benefit of water use. Studies measuring explicitly the marginal benefit function i.e. indicating the change in value due to change in resource input are rarely observed; Daubert and Young (1981) and Duffield et al. (1992) are among few studies estimated marginal benefit function for recreational uses of water.

2.2.4.2 Water valuation studies at the study sites

Studies related to valuation of water resources in Bangladesh are rare. Alam and Marinova (2003) estimated total economic value of Buriganga River cleanup project using CVM technique and Chowdhury (2005) estimated the scarcity value of irrigation water to farmers of Bangladesh dividing the whole country into several regions and compares the value with that of India for in the Ganges-dependent districts of both the countries.

No study is found estimating water value for Konto basin; however, few studies measured water value for the Brantas River basin for water allocation and management purpose. These studies include Rodgers and Hellegers (2005); Rodgers and Zaafrano (2002).

2.2.5 Marginal value analysis

Aggregated measure of total economic value at a given level of water use is typically inadequate (Griffin, 2006) and provides little help to water managers due to its failure in reflecting equitable distribution of gains and losses among individual uses (Turner et al., 2004). Total value quantification may provide limited justification for water investment decision (Young, 1996); however, efficient resource allocation – water in particular case – concerning trade-off analyses, requires equating marginal values of the resource in its alternative uses (Dinar et al, 1997; Agudelo, 2001; Turner et al., 2004; Gleick et al., 2006; Moran and Dann, 2008). Moreover, only single point assessment of the marginal value does not enable the same level of managerial power as does knowing the full marginal value function (Griffin, 2006). Marginal value functionally depends on the availability of water for the concerned use (Gillian and Brown, 1997).

2.3 Consideration for environment in water allocation

Dealing with ever increasing demands for freshwater and economic and technical constraints and limits over supply augmentation, human has manipulated and altered the natural flow regime to a large extent using several hydraulic structures building across the rivers. The prime role of the river and in fact, the reason of its existence is the natural drainage, where drained water from upstream comes to river and the river-channel carries it to downstream. A minimum flow is critically important for maintenance of the channel for maintaining drainage function of the river system. However, this functionality of the river channel has been largely affected due to altered flow regime. The engineering advancements have brought humanity many benefits; nevertheless, the fundamental characteristic of the rivers – the natural flow regime – has been changed which has had the unforeseen consequences of leading to the worldwide degradation of the rivers (Bunn and Arthington, 2002; Hughes, 2003; Tharme, 2003; King and Brown, 2006). Changing flow regime has far reaching consequences not only on the loss of ecosystem integrity but also on the links between human and rivers. Especially the human-river linkage are well-built in developing countries, where rural livelihoods respond to the annual hydrological cycle and many cultural, religious and recreational ties to the river bear deep meaning that all have had affected due to traditional basin development practices (King, 2009).

However, increasing concerns and growing awareness over environmental sustainability and maintaining ecosystem integrity and river's functionality (natural drainage) persuade the water managers to recognize the need of providing certain amount of flow in the river with an acceptable level of quality while allocating water to various sectors. Such flows are often considered as environmental flow or instream flow which tries to mimic the natural flow regime in order to ensure the environmental sustainability as well as the provision of ecosystem goods and services provided by the rivers on which humanity relies in numerous ways.

2.3.1 Global crisis and today's imperative

Alike the history of over thousand years, still the river flow that drains into the sea is often viewed as wastage and in several places the entire river water is shared among the off-stream users leaving the rivers dry. The circumstances remind once again the well known quote from Winston Churchill in 1908 (cited in Postel and Richter, 2003):

> *"One day, every last drop of water which drains into the whole valley of the Nile … shall be equally and amicably divided among the river people, and the Nile itself … shall perish gloriously and never reach the sea" – Winston Churchill.*

Water requirement for the natural environment is in general ignored in the traditional water management and planning (Gleick, 1996; Gleick, 2003; IWMI, 2005) even though the environment is showing a continuous degradation. The repercussions of such practices in managing the river basins change the dynamic movement of water and sediment of a free flowing water body, which results an alteration of habitats for aquatic and riparian species with an ultimate loss of the ecosystem goods and services those a flowing water body provides (Poff et al., 1997; King and Brown, 2006). World Commission on Dams (2000) reports at least 20% of the world's freshwater fish have become extinct, threatened or endangered. Gleick (1996) noted that in global scale there are more than 700 species of fish which are considered to be threatened with extinction. Degradation of the freshwater habitat and the rate of species loss are estimated to be five times greater in aquatic ecosystems than in terrestrial ecosystems (Ricciardi et al., 1999).

Unabated degradation of the natural water bodies urged the scientists started thinking on provision of flow for those water systems. Researchers came up with the concept of limiting the flow diversion for human use up to a point that can maintaining the integrity of the ecosystem or an accepted level of degradation (Tharme, 2003). First initiated in late

1940s in the USA for the interest of a single issue of recreational fishermen, the concept of environmental flow (EF) actually gained the momentum in 1970s mainly owing to legislative changes at the peak of dam building era in the USA. Outside the USA, aquatic scientists also took the assignment to defining the water requirement for the environment and ecosystem around late 1980s (King et al., 2003). Australia and South Africa is the pioneer in defining and applying this knowledge in the field (Tharme, 2003). European Union established the Water Framework Directive (WFD, 2000) in October 2000 to achieve good qualitative and quantitative status of all water bodies (including marine waters up to one nautical mile from shore) by 2015. The WFD sees water management as a single system: River basin management where a general protection of the aquatic ecology, specific protection of unique and valuable habitats, protection of drinking water resources, and protection of bathing water are integrated for each river basin. At present in many places, environment is treated as a competing user of the fresh water with other human needs in several countries of the world (King and Brown, 2006).

At the early stage, environmental flow was mainly focused and set based on single species or single issue-need such as ensuring the salmon/trout number for the recreational fishermen. However, preserving the habitat for the target species, several biological and ecosystem factors need to be considered and ensuring flow without consideration of those factors might fail in achieving the target. Besides some argument on ensuring flow for the critical species will probably serve most other ecosystem needs, a vast body of scientific literature reveals that it may not necessarily be so. Environmental flow therefore should focus the entire ecosystem's need. In line with this concept and increasing awareness and interest for restoration and protection of the riverine ecosystem, environmental flow assessment (EFA) methodologies increasingly took a holistic approach (Instream Flow Council, 2002; Brown and King, 2003). A further shift in EFA has taken place from objective based prescriptive approach to an interactive approach for establishing relationship between river and river system (Tharme, 2003). This relationship between river and riverine ecosystem may then be used to describe environmental/ecosystem implications for further translating into socioeconomic implication for various flow scenarios. Thus, interactive methodologies assist in exploration of tradeoff of several water allocation alternatives.

The current paradigm of water resources management is to rethink water use with the objective of increasing the productive use of water in all use sectors including environmental uses (King, 2009). Water scientists are continuously working in defining the development space where a limit on flow modification is imposed to maintain certain level of ecosystem integrity (Figure 2.5). Environmental flow provides an opportunity to make a compromise between river basin development in one hand and keeping the river health to an agreed level on the other. The key question here is to define the development space; however, sustainable use of the resource can provide the opportunity of shifting the development space towards right by pulling up the ecosystem integrity line (dotted one in Figure 2.5) upwards. Along this line of sustainable use of the resource, a new way of thinking beyond 'business as usual' is imperative. Unsustainable use of river and subsequent loss of ecosystem integrity through non-ensuring environmental water requirement would result several heavy-medium and long-term cost to the society such as public health risks, loss of food security and damage to livelihood, loss of biodiversity, and increased water-related conflicts (IWMI, 2005).

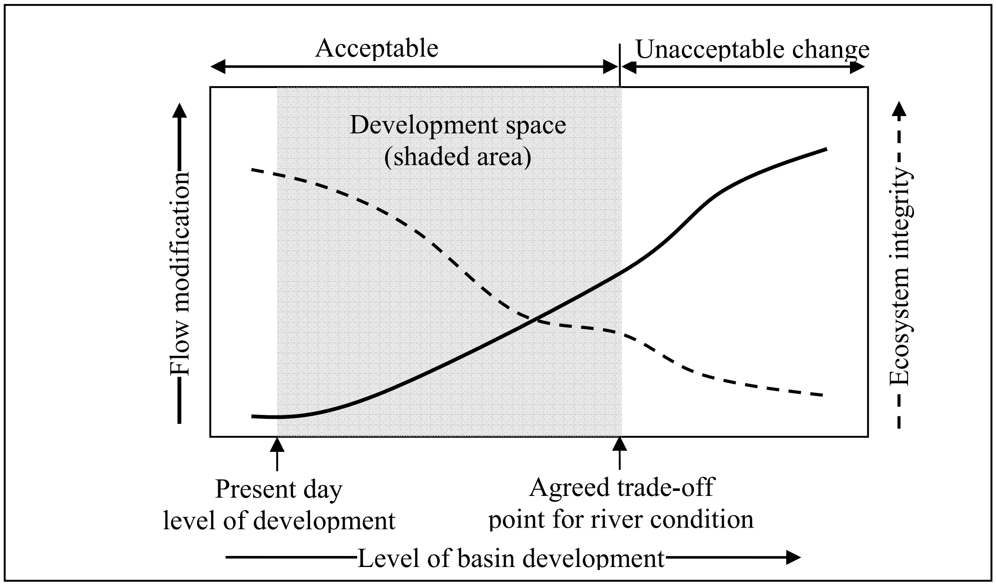

Figure 2.5 Concept of development space considering negotiated limit of river basin development
Source: Adapted from King (2009)

2.3.2 Competition for fresh water – Conflict between human and nature

Approbation and recognition for environmental water requirements already have received a substantial momentum; however, rivers are still showing the sign of drying up (Das Gupta, 2008). Ever growing demands of water for human and developmental needs are increasingly generating pressure on environmental allocation. David Molden from IWMI correctly noted –

> *"It is possible to reduce water scarcity, feed people and address poverty, but the key trade-off is with the environment" – CGIAR News Release, August 21, 2006.*

Reallocation of water from off-stream use to environmental use are observed in few places (Hollinshead and Lund, 2006); however, conflicts based on the perceived needs of ecosystems versus human for fresh water are increasingly reported in the news and came in several literature. Globally agriculture consumes the largest share of freshwater and the demand is expected to be doubled by 2050 (Falkenmark and Galaz, 2007). The ever-growing demand for more water to grow more food, under poor irrigation use efficiency in general, is a real threat in several water-stressed developing countries. Keeping adequate water in the rivers to sustain the ecosystems makes the situation further complicated. In the second World Water Forum this issue was raised and discussed deeply while Global Water partnership (2000) noted the rising conflict between agriculture and environment would be one of the most serious problems to be undertaken in the early 21st century.

Smakhtin et al. (2004) might be the first in estimating the global environmental water scarcity and they stated that about 1.4 billion people live in river basins where current water uses are in conflict with environmental water demand. Smakhtin et al. (2004) reported several major river basins including the Ganges would move into a higher category of human water scarcity, if environmental water requirements are to be satisfied. Any transition from the environmentally scarce to environmentally safe will only be possible if water productivity is significantly increased in agricultural sector and if the allocation of water for environmental purposes is made a common practice in river basin management.

2.3.3 Environmental flow and water allocation

Water resources related threats are increasingly being observed from water scarcity, heavy pollution loads, wide spread public health problems, and serious damage to world's ecosystem. In finding new and innovative approaches international community recognized and reached to a consensus in favor of Integrated Water Resources Management (IWRM) as an appropriate approach to address the threats posed to water resources even though countries implementing IWRM is rare and in fact they do only integrated water management, which deals with multi-faceted issues of a sectoral water use. However, several countries are trying to reach out to bring the process for implementing IWRM. Integrated water resources management promotes overall water resources development in the view of maximizing resultant economic and social welfare in an equitable manner without compromising the sustainability of vital ecosystems (GWP, 2000). Progress of IWRM implementation during the last decade points towards growing global concern related to lack of practical basis of IWRM concepts. Forging a right balance between competing human uses of water, while ensuring environmental health and productivity, is a cornerstone of sustainable development and implementing IWRM, where environmental flow plays the central role. With the concept of environmental flow, IWRM identifies the environment as an individual sector with its own right of using water at a basin scale.

Within the framework of IWRM environmental flow helps ensuring water allocation for the environment in development planning, especially involving large infrastructure, and is seen as an integral to sustainable water management. With a better understanding of environmental requirements and the potential trade-offs with other uses, decision-makers are able to make informed decisions on water allocation to competing users. The trade-off point is not a technical one but a societal choice – a value judgment of how much people are willing to lose in terms of ecosystem services in order to gain the benefits of development. Environmental flow approach provides the roadmap in defining negotiated in-stream flow requirements, considering the implications for infrastructure development, assessing costs and benefits, nurturing a supportive institutional and policy framework and generating political consensus for changes.

Policy formulation related to EF implementation in water resources management is still in its infancy in much of the world, especially in developing countries (Tharme, 2003; Moore, 2004). In particular for Asia, main challenges to adopting EF include lack of understanding of socio-economic benefits and costs involved with environmental water allocation, lack of political will to support EF implementation along with management, legal and institutional constraints, explored through primary survey to water professionals (Moore, 2004).

Factors likely to limit the adoption of EF also include lack of awareness from the key stakeholders. In addition to just recognition of the concept, awareness should be extended to various aspects including awareness of the costs and benefits of implementation, the consequences if the concept is not considered, and the trade-off between social, economic and environmental objectives within a river basin. It is therefore extremely important to realize the societal cost and benefit from environmental water allocation by all the stakeholders. This concept gets reinforcement when analyzing the reasons behind successful implementation of EF in some countries where importance of flows to local livelihoods is taken with due regards (Moore, 2004). Community members and social organizations, as well as other key actors within a river basin, therefore need to be meaningfully engaged in the development of an EF program.

2.3.4 Methods to assess environmental flow

In general, an environmental flow assessment needs to include (i) the goal (such as non-degradation), (ii) resources (such as fish species), (iii) unit of measurement (such as cusec discharge or habitat in weighted usable area (WUA)), (iv) benchmark period (such as a 10-year period of record), and (v) protection statistic (such as the median habitat value for April). Estimation of EF gives the direction to water managers understand the amount of flow necessary for sustainable river ecosystem and enable them to integrate this need with other human needs, because trade-offs are often required for meeting the both demands (Richter et al., 2006).

Since 1960s and 1970s an assortment of methods to assess the EF requirement has been developed mainly by the agencies having regulatory responsibility related to water development and management. The methods differ in scope of application and data requirements. Not having a clear and widely accepted definition of EF, different methods are practiced by the scientists to assess the environmental flow for different water resources system planning. Tharme (2003) reported 207 methods from 44 countries in her recent study and she grouped them into four categories. In addition to this, documentation from IUCN and World Bank are also available on environmental flow assessment methodologies and presented into some categorical ways. Environmental flow methodologies with its categorization are represented in Table 2.4.

Stalnaker et al. (1995) divided environmental flow assessment problems into two categories depending on the objectives of the decision process: standard-setting or incremental. The analyst therefore in a standard-setting problem is called on to recommend an instream flow requirement to guide general and usually low-intensity decision setting, a limit below which water cannot be diverted. This process might be called preliminary planning. An incremental problem on the other hand refers to a high-stakes negotiation and high-intensity decision making over a specific development project. The term ‘incremental’ implies the need to answer the following question: what happens to the variable of interests (e.g. aquatic habitat, recreation value) when the flow changes?

The categorization by IWMI (Tharme, 2003) is based on the biophysical input data requirement rather methodological characteristics, which seems most logical and followed for brief discussion.

Table 2.4 Categorical classifications and methods of environmental flow assessment

Organization & Author	Categorical classification	Method (Prominent example)
IWMI (Tharme, 2003)	Hydrologic index	Tennant method
	Hydraulic rating	Wetted perimeter method
	Habitat simulation	IFIM
	Holistic methodologies	BBM, DRIFT, expert panel, bench marking method
IUCN (Dyson, 2003)	Look up table	Hydrological method (Q95 index) Ecological method (Tennant method)
	Desktop analysis	Hydrological method (Richter method) Hydraulic method (wetted perimeter method) Ecological method
	Functional analysis	BBM, Expert Panel Method, Benchmarking Method
	Habitat modeling	PHABSIM
	Approach type	Expert team approach, stakeholder approach
	Framework type	IFIM, DRIFT
World Bank (Brown and King, 2003)	Prescriptive approach	Hydrologic index method (Tennant method) Hydraulic rating (wetted perimeter method) Expert panel Holistic (BBM)
	Interactive approach	IFIM, DRIFT

2.3.4.1 Hydrologic index methods

These are the most simple, less resource and data intensive, rapid and widely used, but low resolution assessment of environmental flow. Hydrological methods correspond to standard setting problems (Stalnaker et al., 1995 classification) mainly related to fisheries. These methods are also categorized as desktop, lookup table (Table 2.4). The techniques are considered suitable for long-range planning of instream flows for fisheries in a low-intensity situation when not much detail is required and where a quick, reconnaissance-level, office-type approach would be used. These methods use only historical flow data, usually in the form of naturalized, historical monthly or daily flow records.

The most renowned method in this group is the Tennant (1976) method originated from USA where eight classes of flow classifications were established by Tennant after analyzing a series of field measurements and observations to correlate habitat quality with various percentages of mean annual flow (MAF). His recommendation for instream flow for various condition of habitat quality on a seasonal basis is presented in Table 2.5. Seven of these classifications characterize habitat quality for fish and wild life and the eighth provides a flushing flow.

Table 2.5 Percentages of Mean Annual Flow (MAF) required for maintaining the specific habitat quality as proposed by Tennant (1976)

Environmental status or Habitat quality	Percentage of MAF	
	Low flow season	High flow season
Flushing flow	200	200
Optimum range	60-100	60-100
Outstanding	40	60
Excellent	30	50
Good	20	40
Fair or degrading	10	30
Poor	10	10
Severe degradation	<10	<10

Other hydrologic methods include flow duration curve (FDC) method, constant yield method (Jowett, 1997; Karim et al., 1986) and Range of Variability Approach (Richter et al., 1997). The FDC method utilizes historical records to construct flow duration curves for each month to provide cumulative probabilities of exceedence for various flows. Based on at least 20 years of daily flow records, a flow recommendation is made for each month. This method includes the provision to eliminate abnormal events, after which the recommended flow for instream protection may be set at 90th percentile for low flow months and the 50th percentile during high flow months. Since the level of protection is implicit in the magnitude of percentage, different exceedence probabilities have been used in specifying EF, e.g. in New Zealand the flows that equaled or exceeded 96% of the time have been used to assess ‘minimum’ flows.

The Range of Variability Approach (RVA) is intended for setting flow target on rivers where protection of the natural ecosystem is the primary objective. A fundamental principle is to maintain integrity, natural seasonality and variability of flows. The method identifies the important components of a natural flow regime for the river, indexed by magnitude (of both high and low flows), timing (indexed by monthly statistics), frequency (number of events) and duration (indexed by moving average minima and maxima). RVA takes account 32 hydrologic parameters as the Indicator of Hydrologic Alteration (IHA) to assess the environmental flow. RVA is the only method in this group which supports the flow regime concept given by Poff et al. (1997). The 32 statistical hydrologic parameters used in RVA are presented in Table 2.6.

2.3.4.2 Hydraulic rating methods

These methods are little more than basic standard setting techniques but not quite incremental. Commonly used hydraulic methods consider the variation in wetted perimeter with discharge. It establishes a function between wetted perimeter and discharge, depth and velocity to set minimum discharge for fish production and rearing (including spawning). The wetted perimeter technique selects the narrowest wetted bottom of the stream cross-section that is estimated to protect the minimum habitat needs. It is relatively a quick and cost-effective method and useful as a planning tool at catchment scale or greater. The Wetted Perimeter Method developed by Reiser et al., (1989) is the most commonly used hydraulic rating method.

Table 2.6 Indicator of Hydrologic Alteration (IHA) parameters used in RVA analysis

IHA	Unit	No of parameters
Mean flow of each calendar month	m^3/s	12
Annual 1 day maximum and minimum flow	m^3/s	2
Annual 3 day maximum and minimum flow	m^3/s	2
Annual 7 day maximum and minimum flow	m^3/s	2
Annual 30 day max and min flow	m^3/s	2
Annual 90 day maximum and minimum flow	m^3/s	2
Base flow condition (annual 7 day minimum flow divided by annual mean flow)	---	1
Julian date of annual 1 day maximum and minimum flow		2
Number of high pulses and low pulses in each year		2
Mean duration of high pulse and low pulse	days	2
Rise rate	$m^3/s/d$	1
Fall rate	$m^3/s/d$	1
Number of flow reversal		1
Total parameters		32

Source: Richter et al., 1996.

2.3.4.3 Habitat simulation methods

Unlike the assessment by hydrological or hydraulic methods of single instream flow recommendation, habitat simulation methods allow the analyst to display impacts on the resource of interest for any given flow. However, hydrological or habitat methods are better to use when the ecosystem is poorly understood and a better level of protection is needed because of the single species focus or a specific instream use treated by the habitat methods (Jowett, 1997).

This method uses two types of tools, either statistical analyses to correlate environmental features of a stream with fish population size, an example of this analysis is habitat quality index (HQI) or to link open channel hydraulics with known element of fish behavior, like Instream Flow Incremental Methodology (IFIM). The main component of IFIM is Physical Habitat Simulation System (PHABSIM), presented by Bovee (1982). PHABSIM is the most commonly applied habitat simulation methodology.

2.3.4.4 Holistic methodologies

This group of methods is fully ecosystem-based and incorporates hydrologic, hydraulic and habitat simulation models. This is an integrated assessment of flow need based on expert judgment or collective experience of an expert panel. The panel of experts normally comprises of hydrologist, geo-morphologist, aquatic botanist, fish biologist and in most cases one or more community representatives.

The Building Block Methodology (BBM) developed in South Africa (King et al., 2000) and Holistic Approach (Arthington et al., 1992) in Australia are most widely used holistic methods which were developed in collaboration and share of the same basic tenets and assumptions. Recently another holistic methodology has been developed in South Africa which comprises of four modules (biophysical, social, scenario development, and economic) with the name of DRIFT (Down stream Response to Imposed Flow Transformations) (King et al., 2003).

In addition to these four broad groups of methodological classification, Tharme (2003) noted some other individual methods which are not exactly fitting under any of these four groups and she grouped them as ‘combined’ and ‘others’. Based on her calculation the relative proportions of total 207 methods grouped in the six types are shown in Table 2.7.

Table 2.7 Relative proportions of environmental flow methodologies of each type

Methodology type	**Percentage**
Hydrological	29.5
Habitat simulation	28.0
Combination	16.9
Hydraulic rating	11.1
Holistic	7.7
Others	6.8
Total	100 (207 individual)

Source: Tharme, 2003

2.3.5 Evaluation of the EF assessment methods

Although the environmental flow is not an old concept, a chronological analysis shows that there is a clear but distinct difference between the initial stage and the recently used methods for environmental flow assessment. At the beginning, EF was centered on a minimum flow concept for an entire season (wet or dry) e.g. Tennant method developed in 1976. EFA methods were then turned from minimum flow to species need objective. The development period of hydraulic rating (Wetted Perimeter method on 1989) and habitat simulation (PHABSIM on 1982) are almost in the same period of time (80s decade) which were mainly focused on some fish species.

A seminal publishing by Poff et al. (1997) “The Natural Flow Regime” brought significant change in EF concept. He pointed out the flow regime (quantity, duration, timing and variability of flow) is the key driver for river as well as riverine ecosystem (Poff et al., 1997; Richter et al., 1997; Bunn and Arthington, 2002). On the same time Richter et al. (1997) developed the Range of Variability Approach (RVA) – a hydrology based method which takes care of flow regime by introducing 32 ecologically relevant hydrologic parameters in EFA method.

Methodologies then turned into the holistic approach in this decade (BBM in 2000 and DRIFT in 2003) which consider the whole ecosystem need rather than flow requirement only for the rivers. In conclusion the evolution trend of EFA techniques can be summarized as (i) from a single issue to river flow regime (ii) from single species need to holistic ecosystem approach, (iii) from instream to riverine ecosystem requirement and (iv) from a hydrological field of research to an interdisciplinary one (Shiau and Wu, 2007).

Another important concern is choosing of the right EFA method. Protection of flow regime for every water resources management project is a unique challenge and the existing EFA methods may not suit always to the specific country, region or basin problem (Smakhtin et al., 2006). Choosing EFA method also depends on the technical consideration such as data availability (only flow data to whole ecosystem information), extent of the study area, expertise available, prevailing time (which can vary from ½ month to about 36 months) and financial constraints and level of confidence required. Mainly, the purpose of flow assessment and the intended use of the results act as guiding criteria in selection of environmental flow assessment method. Considerable negotiation and trade-off between environment and development issues might be required for large and controversial projects whereas a single value may satisfy the planning purpose.

Especially for the developing country perspective, Tharme and Smakhtin (2003) (cited in Smakhtin et al., 2006) noted that there are distinct gaps in environmental flow knowledge and practice in water resources management and most of the cases there exists the lack of technical and institutional capacity to establish environmental water allocation practices. However, to promote the environmental flow concepts, it is very important to change the current perception on the interest for environment along with an increased awareness and country specific case studies (Smakhtin et al., 2006).

2.4 Modeling water allocation

The uneven distribution of precipitation and river flow (i.e. water supply) over the spatial and temporal scale is being affected synergistically with climate change and/or variability phenomenon. In contrary, water demands are more of a time-varying event. Very often the high water consumption period does not coincide with the times of abundant rainfall or stream flow. Along with this uneven distribution of water supply and demand, the ever increasing freshwater demands from growing population, urbanization and industrialization frequently result conflicts between users with the scarce water resources in many places. Water management is therefore becoming increasingly controversial in many places of the world. Involvement of wide variety of interests, stakeholders and management options have posed challenges to traditional approaches to managing the water resources; hence integrated water management is increasingly apparent (Heinz et al., 2007).

Reduced flow and water scarcity in rivers result loss of integrity of the aquatic ecosystem and reduced supply of freshwater sustained goods and services to the society, which has a far reaching impact on poverty eradication, regional to national economy and lastly on sustainable development. In line with managing such problem, reallocation of water from offstream use to environmental and instream uses might be required, prescribed and has been taken place in few cases. However, such actions can be considered myopic unless it is based on concrete and acceptable allocation strategy and plan. Hence, water allocation not only among offstream users but also between in- and off-stream sectors currently becomes central in managing the water resources properly.

Water allocation in general aims to maximize the benefits to the society from the resource. However, the general objective has implication to the more specific objectives such as social, economic and environmental with the corresponding principles of equity, efficiency and sustainability, respectively (UNESCAP, 2000). Equity indicates a fair sharing of water resources in river basin at all level (local, national and international) and among all users. Since different people may have different perceptions for the same allocation (Young, 1994), a pre-agreed tenet is important to be placed for allocation of water, especially under water scarce situation. Efficiency guides to a financially sustainable use of water resources; however, it also implies the fair compensation for water reallocation between users. Sustainability on the other hand advocates the environmentally sound use of the resource. Water allocation follows either of the principles of water right such as riparian right, prior appropriation rule, public ownership (Savenije and Van der Zaag, 2000) along with a number of mechanisms such as administrative, user-based, marginal cost pricing and water market (Dinar et al., 1997).

2.4.1 Water allocation models

Simulation and optimization models are common and widely used in the field of water resources management and in particular for allocation practices. Simulation models simulate water resources behaviors in accordance with a predefined set of rules; e.g. AQUATOOL (Andreu et al., 1996) that allows user-defined nodes, links, operation rules and targets. Water quality simulation models are also available such as QUAL2E (EPA, 1996). MIKEBASIN (DHI, 2001) coupled with GIS is a comprehensive hydrologic modeling tool that provides basin scale solution. Optimization models optimize the overall system performance based on predefined objectives and constraints. However, such models are often embedded with simulation component to calculate hydrologic flows and mass balance. Optimization models are useful when improvement of the system performance is the target (McKinney et al., 1999).

From intra sectoral to inter-sectoral and from single objective to multi-objective optimization problems came across the literature with the use of different techniques (like Linear Programming, Non-Linear Programming, Dynamic Programming, and recently Genetic Algorithm) to solve the optimization problem. Optimization models concerning irrigation water use received considerable attention due to high importance and consumption of freshwater in irrigation sector (Brouwer and Hofkes, 2008).

Amir and Fisher (1999) developed an optimizing model for analyzing agricultural production under various water quantities, qualities, timing, pricing and pricing policies. Reservoirs are important component in water resources system. Several models dealing optimal reservoir operations and water allocation are found in literature with single or multi-objective goals; examples include Loucks et al., 1981, Vedula and Mujumdar, 1992; Vedula and Kumar, 1996; Chatterjee et al., 1998.

Goulter and Castensson (1988) proposed a model that maximizes the total output from allocating water shortage among three competing users (hydro-power, irrigation, urban supply) in the Svarta River Basin in Sweden using method-of-weights.

Deshan (1995) worked for optimal allocation of water resources through large-system Hierarchical Dynamic Programming (LHDP) where the net economic benefit for a river basin is maximized from the water allocation among consumptive uses. The study considered the non-consumptive uses as constraints and these uses were prevention of flood, carrying silt off, prevention of ice, hydropower and navigation.

Cardwell et al (1996) developed a multi-objective optimization model to satisfy fish and human water needs. Maximize fish population and minimize the water supply shortfall were the objective functions.

Yen and Chen (2001) used Linear Programming for optimization of water allocation based on forecasted demand in South Taiwan. They optimized the allocation problem using three strategies namely priority of water use benefit, water right and purpose of usage where instream flow was taken as one of the constraints.

Ndiritu (2003) used a multi-population genetic algorithm to optimize a system of two reservoirs in Mkombo catchment from South Africa. Optimization was aimed at minimizing the penalty from non-supply of water and four cases were analyzed. The cases were generated with various combination of optimizing reservoir capacity, demand and rule curve.

Wang et al. (2004) worked on a fair allocation objective for the Amu Darya river basin by Lexicographic Minimax approach. Instream flow requirement is taken as one node point in the minimax approach. The large linear programming problem was solved by GAMS coded algorithm.

Chang et al. (2005) used both binary and real coded genetic algorithm for optimizing the reservoir operating rule curve where curves were assumed piecewise linear function. They did not take in to account the environmental flow requirement to develop the rule curve.

By using EPIC software Schluter et al. (2005) determined optimal water distribution between competing water users in the complicated network of the Amu Darya River under physical and management constraints.

Suen and Eheart (2006) used Non-dominated Sorting Genetic Algorithm II (NSGA-II) for the multi-objective optimization of water allocation from a reservoir. They came up with the optimal trade-off between human needs and ecological flow regime maintenance. Based on the intermediate disturbance hypothesis they calculated the ecosystem water needs and they applied Fuzzy set theory to represent the degree of disturbance levels.

Shiau and Wu (2007) employed multi-objective genetic algorithm to determine the Pareto-optimal solutions for environmental flow schemes for a weir operation where they incorporated inter and intra-annual flow variability. They used range of variability approach to estimate the environmental water requirement.

Due to the complexity of water allocation at the regional or basin level, economic efficiency is an interesting and increasingly being used criterion to the basin managers in allocating water optimally among the competing users. Several custom built models including generalized DSS are available on economic efficiency based water allocation model, details are provided in the following sections.

2.4.2 Economic efficiency and hydro-economic modeling in water allocation

Because of the scarcity of the resource, water needs to be allocated efficiently, i.e. maximizing the value that water resource provides to society (Harou et al., 2009). While allocating water, economics offers methods in appraising efficiency and equity. In this vein, water is increasingly considered as an economic good (Briscoe, 1996; Young, 2005). Water engineers are becoming interested looking into not only how water resources policy affects the entire economy but also how economics affects water resources management.

Engineers traditionally estimate the water requirements and evaluate the cost of infrastructures planned and built to garner the benefit from water uses. In a non-economic system model, water-use demand is considered as fixed water "requirements" based on the static view of water demand that leads to over-design of infrastructures. However, a wider view is essentially required in managing the scarce water resources in particular when the resource is entering into the 'mature' phase – the 'mature water economy' (as defined by Randall, 1981). Economics helps water professionals in shifting the concept of a discrete volumetric demand to a demand function. In this concept, benefit from water use changes with the quantity and type of water use. Shortcomings of the terms like water requirements or needs are increasingly becoming evident in this regard (Griffin, 2006).

Since the traditional engineering system operation and resource allocation faces difficulty in meeting the sustainability issue of the resource system at basin scale, innovative system oriented analysis deems necessary from the science community (Cai, 2008). The inherent intricacy of the water system with many interdependent components and the interactions between water and economy can suitably be captured using mathematical models linking relevant hydrology and economic 'laws' of supply and demand. Such integrated hydrologic and economic models hereafter called 'hydro-economic model (HEM)' are well suited to support decision making, benefit valuation, plan design, alternative evaluation and institutional design with policy issue (McKinney et al., 1999; Lund et al., 2006; Cai, 2008; Harou et al., 2009)

2.4.2.1 Features of HEM

Including the economic concept at the heart of the water resources management, HEMs represent the hydrologic, economic, engineering and environmental aspect of a water resources system in a coherent framework (Harou et al., 2009). Hydro-economic models can be characterized as economic optimization model embedded with hydrologic simulation models to allocate water optimally and efficiently with consideration of spatially distributed water resources systems, demand sites, management options and water-use benefits in an integrated manner. Such models also provide a framework for policy design incorporating the economic aspects such as water pricing in particular for the water-stressed basins (Ward and Pulido-Velazquez, 2008).

The individual demand function of each water use determines the water allocation in hydro-economic modeling. In general, the model is schematized as a node-link network representing the spatial relation between various demands sites in the river basin. Economic demand functions are incurred at each node. Including such economic water demands distinguishes HEMs from the engineering models that focus on mainly cost-benefit analysis. Hydro-economic models also differ from economy-wide economic models by at least two points; (i) economy-wide economic models account the shocks that affect the entire economy due to water resources policy; however, HEMs consider the effects that economics results on water resources system, (ii) economy-wide models do not represents spatially distributed water resources system (Harou et al. 2009).

2.4.2.2 HEM design

In designing HEMs, water resources systems are modeled as network of storage and junction nodes. The conveyance links join the junctions and represent the river reaches, canal, pipelines etc. The demand sites that incur a cost or benefit from water use are presented as node. Economic benefit functions for water uses (i.e. at each node) provide the economic information to the model for a particular model time-step.

Estimating the net benefits of individual water use at each node and incorporating those benefit functions with the hydrological components are the fundamental in designing HEMs. Two approaches are common; (i) first estimating the benefit functions for the water demand sites and include them in the HEMs as separate input commonly known as modular or compartmental approach (e.g. Draper et al., 2003), or (ii) the economic benefit estimation process endogenously embedded within the model known as holistic modeling (e.g. Cai et al., 2003). Estimating the net benefit functions for the first case often use either empirical water demand functions obtained by using econometric approaches (e.g. Diaz et al. 1997; Rosegrant et al. 2000; Ringler 2001) or by external simulation or optimization models that take account details of the production processes within the demand sites (e.g. Booker and Young 1994; Mahan 1997; Reca et al., 2001). The advantages of the modular approach include ability to go into more detail of each sub-model and individual update or development of the sub-models as required.

Since optimization is the unifying paradigm for most of economic analyses, HEMs commonly use optimization technique solved analytically, with mathematical programming or by heuristic approach such as evolutionary algorithms. Hydro-economic models are in general deterministic in nature (Harou et al., 2009). Such models tend to implement variations of deterministic optimization that provide results from time series operation of optimal allocation such as storages or flows. The spatial domain of the HEMs varies from a single farm to a sub-basin or an entire river basin that often crosses political boundary. Economic models of natural resources are normally spatially lumped; however, HEMs are in general semi-distributed (lumped as sub-basin/regional scale) and presented as node-link. The temporal domain ranges from few days to even decades for planning purposes. Often HEMs consider the time horizon as one year subdivided into time-steps such as months.

2.4.2.3 Application of HEM for efficient water allocation

Hydro-economic modeling applications cover a wide range of water resources problems at different locations with a variety of water uses covering both off- and in-stream uses. The offstream uses are usually consumptive e.g. municipal, industrial and irrigation. The instream uses include hydropower, recreation and navigation. Inclusions of economic benefit function for environmental water uses and for minimum environmental flow in the HEMs are very rare in literature. Water quality is rarely explicitly incorporated in HEMs owing to the difficulty and complexity in quantitative assessment of economic effect of this issue to the overall modeling system.

Several basin scale hydro-economic modeling studies are available through literature; e.g. Conway et al. (1996) worked on the Nile Basin, Egypt. Their analyses focused into three scales: global depicting climate change issue, regional deals with land use patterns, and water management at basin scale.

De Wit (2001) developed model (PolFlow) for the Rhine and Elbe river basins in Europe showing policy analysis related to nutrient pollution. Ward et al. (2006) estimated the economic impact of alternative policies for drought management for the Rio Grande river basin.

Rosegrant et al. (2000) and Cai and Rosegrant (2004) presented the HEM for the Maipo river basin in Chile. Salinity balance and crop growth are embedded within the optimization model, reservoir operation and irrigation scheduling. The developed model reflects the interrelationships among essential hydrologic, agronomic, and economic components and finally reveals the economic and environmental consequences of alternative policy choices.

Rosegrant et al. (2000) for Maipo river basin, Draper et al. (2003) and Jenkins et al. (2004) for California water supply system and Ward et al. (2006) for the Rio Grande Basin analyzed water transfers and water markets and estimated the social and economic gains from improvement in the allocation and efficiency of water use through HEMs.

Fisher et al. (2002) included social policies and institutional realities as constraints within the HEM. Babel et al. (2005) allocated water according to maximize equity and net economic benefits. Using HEM, Ward and Pulido-Velazquez (2009) suggested for two-tiered water pricing system for the basic needs with a low price and full marginal cost for the discretionary uses.

HEM studies (e.g. Draper et al. 2003; Harou and Lund, 2008) also adopted the sustainability criteria such as requiring storage at nodes to be the same at both the beginning and end of the period of analysis

Babel et al. (2005) demonstrated hypothetical example of optimal water allocation between competing users by SICCON technique where socio-economic, environmental and economic aspects were considered and environmental sector's economic return was taken as the average of all other sectoral returns for the illustration.

Predominantly the HEMs considered the environmental water requirements as a low-flow constraint due to difficulties in valuing the environmental services, e.g. Jenkins et al. (2004). However, Diaz et al. (1997) considered the environmental and recreational services with value function in water allocation.

2.4.2.4 Software application in HEM

Hydro-economic models in general run in either of the two different environments; custom (user defined) built model or use of model platform or generalized Decision Support System (DSS). Custom models are widely used and are commonly formulated within a generic modeling system (commercial examples of such systems include GAMS, APML) and that links to some commercial solver, e.g. MINOS, CONOPT. Advantages of this system embrace flexibility, transparency and self documenting facilities. On the other hand, model platform links the existing custom model to a generic user-interface and data manager. A few generalized water resource DSS purposely made for hydro-economic modeling application are also available and can be used when custom model formulation is not required; examples include MITSIM (Strzepek et al., 1989), AQUARIUS (Diaz and Brown, 1997), AQUAPLAN (Tilmant et al., 2008). Few other DSS exist which can be configured to include hydro-economic components such as AQUATOOL (Andreu et al., 1996), MODSIM (Labadie and Baldo, 2000), MIKE BASIN (DHI, 2001), WEAP (Yates et al., 2005). A brief evaluation of some available HEM is presented in Table 2.8.

2.5 Concluding remarks

- It is evident that currently allocation of water resources is an important global issue where management seeks to maintain efficiency, equity and sustainability while allocating water among various uses.
- Vast body of literature is available on several allocation criteria/bases using both simulation and/or optimization techniques. However, since water economy is already at its mature phase, it needs a wider perspective for water allocation process. Especial attention is required on how economics rules water resources demand and supply for an efficient solution. Incorporating marginal benefit of water uses is essentially required along this line.
- Again several researches are available on ecosystem and instream water services valuation based on established economic theories, but the work incorporating the values of instream water uses in an integrated water allocation model is rare.
- Water allocation models incorporating scientifically assessed environmental water requirements that mimic natural flow regimes are also dearth.

Research gap also exists in valuing and considering the value of flowing water in a river into the allocation model. In the existing HEM studies, researchers have mainly focused on lakes and reservoirs rather than the river flow in estimating the instream water benefits. Harou et al. (2009) identified no application of economic benefit estimation of instream flow in HEM.

Table 2.8 A brief evaluation of few available hydro-economic models

Model	Design	Sector addressed	Addressing env water	Time step	Application to basin	Open source	Remarks	Reference(s)
Custom model	Optimization	Irrigation, M&I, hydropower	Mostly constraint	Monthly	Several	Depends on author(s). At least two are found open source	Application specific, mostly coded in GAMS and link to a solver (MINOS/NEOS)	Rosegrant et al., 2000; Cai et al., 2003; Babel et al., 2005; Ringler & Cai, 2006 etc.
CALVIN	Optimization	Irrigation; urban; hydropower	Constraint	Monthly	California	Yes	Application specific	Draper et al., 2003
Hydroplatform	Links external model	-	-	-	-	Yes	Neither a Model nor a DSS. It's a model platform. Not yet released	Harou et al., 2009
MITSIM	Simulation	Irrigation and M&I	xxx	Monthly	South Western Skane, Southern Sweden	---		Strzepek et al., 1989
AQUAPLAN	Optimum allocation from reservoir (based on MV)	Hydropower, irrigation; M&I, environment	objective	Monthly	Tigris & Euphrates, Zambezi, Mekong, Mile, Mahaweli, Hanjiang, Tana	On request	Mat Lab tool is used	Tilmant et al., 2008
AQUARIUS	Optimization of total value	All off- and in-stream uses	Objective	Monthly		Yes	Full deterministic optimization	Diaz et al., 1997
AQUATOOL	Simulation and Optimization		constraint	Monthly	Segura and Tagus, Spain	Yes	Optimizes storage and risk of failure of each element	Andreu et al., 1996
WEAP	Simulation	All		Daily to annual		Yes		Yates et al., 2005

Hydroplatform – a new type of modeling software. Unlike a modeling system, model platforms do not support model formulation and solution. The model platform scope is limited to entering, visualizing and managing model input and output data

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3 RESEARCH APPROACH AND METHODOLOGY

3.1 Research approach

Since aggregated measure of the total economic value at a given level of water use is typically deficient in managing the resource efficiently as well as only single-point measurement of the marginal value does not enable the same level of managerial power as does knowing the marginal benefit function (Griffin, 2006), this study, therefore aims to develop the total and marginal benefit functions of offstream (such as irrigation, domestic, industrial uses) and instream water direct-uses (such as fisheries, navigation, recreation). Those functions are subsequently used in the water allocation optimization model as the allocation criterion. Moreover, environmental flow requirements for the river are estimated and used as a constraint while allocating water to the uses in several scenarios.

Several water allocation models are found optimizing reservoir rule curve and maximizing benefit or minimizing shortage of water where environmental flow have not been considered properly. Majority of the studies considered a certain amount of flow and often a minimum flow for the river in a yearly basis as a constraint. However, such consideration does not ensure natural variability of flow and fail to maintain the flow regime. This study estimated the monthly environmental flow requirement that mimics the natural flow regime and used in the optimization model.

Finally, the optimization model for water allocation is set up incorporating the developed marginal benefit functions, monthly environmental flow requirement and the water balance in the system and is applied to the study basins. The analyses finally depict the trade-off scenarios between with and without ensuring environmental flow in the system. Figure 3.1 presents the methodological framework coherent with the stated objectives and research approach. Details of the methodology are described in the subsequent sections.

The model is applied to the Teesta river basin in Bangladesh and to the Konto river basin in Indonesia.

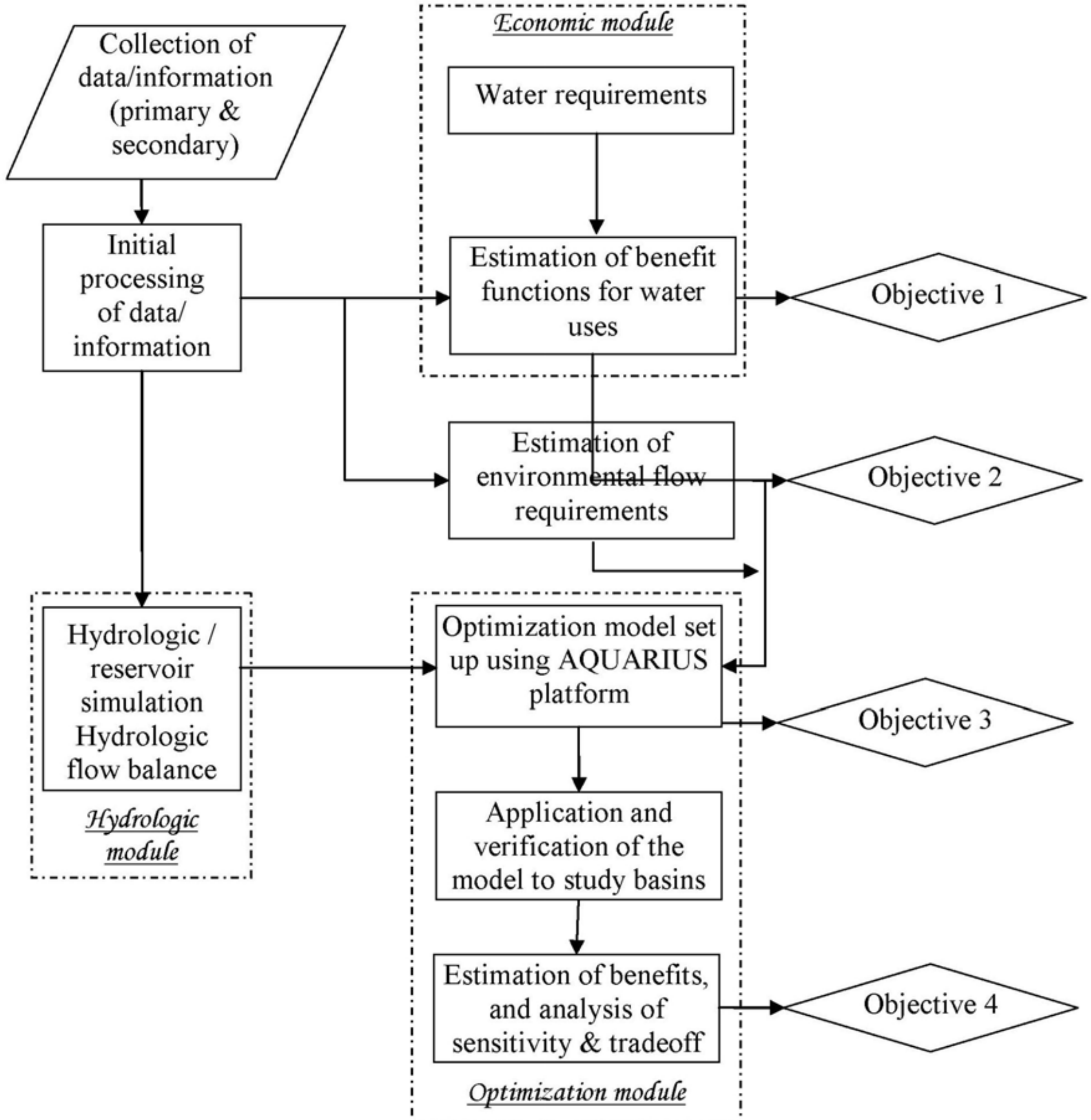

Figure 3.1 Methodological framework for the research

3.2 Developing benefit functions for water uses

Offstream water demands such as municipal and industrial demands are documented from secondary sources. In case of irrigation demands, secondary source data is collected, alternatively analytical approach of estimating the irrigation water requirements is applied (such as using CROPWAT model by FAO). Instream water demand is documented from secondary sources or from primary survey of the water users.

Empirical estimation of demand functions using econometric approaches are often employed in estimating the benefit functions for water users at different demand sites (Diaz et al., 1997; Ringler, 2001). Use of external simulation and optimization models are also common in developing the water-use demand and benefit functions where detail of the production process and characteristics of the demand sites are considered; examples include Booker and Young (1994); Mahan (1997) for the case of irrigation water benefit estimation.

In this study, the relationship between river flow and net economic benefit from each water-use sector are examined. Different approaches of economic analysis e.g. value added, residual imputation (for irrigation and fishery use), direct pricing (for industrial and domestic use), and revealed preference technique for the non-marketed goods and services (e.g. recreational, navigation and casual uses) are adopted based on the data availability of the concerned water use for estimating the total benefit. Using the concept of typical production function, variations in benefit levels due to changes in water availability are estimated and that forms the basis to develop the total benefit function. Quadratic total benefit function as represented by Equation 3-1 is considered for all water uses except hydropower and reservoir recreation, which would facilitate technical consistency for the model when compares the trade-off among all uses across a wide hydrology and policy space. Quadratic benefit function is used earlier by Wang et al. (2008), Ward and Pulido-Velazquez (2008) and others. Marginal benefits of water uses are obtained by taking the first order derivative of the pre-established flow-benefit (total benefit) functions. When several users exist at a single node, the aggregated benefit function for offstream and instream uses are developed by adding vertically the non-competitive instream demands and horizontally the competitive offstream demands (as shown in Figure 2.4).

$$B_{j,t} = b_{0(j,t)} + b_{1(j,t)} * Q_{(j,t)} + b_{2(j,t)} * Q^{2}_{(j,t)} \tag{3-1}$$

Where, $B_{j,t}$ is the water-use benefit at node j and time period t; $Q_{(j,t)}$ is the discharge dedicated to the particular water-use at demand site j in time period t; and b_0, b_1 and b_2 are the coefficients. Valuation techniques are employed to find these coefficients.

Since water availability and supply may fall limited at any stage/time period within a year or during production period, water allocation based on seasonal or yearly water quota (e.g. Mahan, 1997) seems failing to accomplish desired goal. Consideration and allocation practices therefore are being shifted to allocate water optimally among the stages within a season or year. For example, Rosegrant et al. (2000), Ringler (2001), Cai et al. (2003) worked for economic optimal water allocation considering a monthly time step. For this research all the water use benefits are estimated for monthly time step for the individual demand sites.

3.2.1 Municipal and industrial demand site

The terms "community", "municipal", "residential" and "domestic" are often and inconsistently used in the literature indicating the household uses of water; however, this includes some non-residential uses as well. In this subsection the term "municipal" is used to represent the residential and non-residential water uses. Industrial water uses are considered in separate. It is worth noting that both municipal and industrial water uses are private use; however, municipal uses are used as consumers' good and industrial uses are as producers' good (as discussed in Table 2.2). However, market approach is adopted in estimating for both the water uses where the benefit is estimated from an inverse demand function.

The value of water delivered to municipal and industrial users significantly relates with the quality of water. Often water is supplied to these users as treated to the desired level that involves a huge amount of treatment and conveyance cost. This indicates that the value of this commodity is not directly comparable with instream uses unless the treatment and conveyance costs are properly accounted for. In the current study of valuation and allocation of water, it has been assumed that all the municipal and industrial users receive the treated water.

In general municipal and industrial sectors use much less water than agriculture; however, their willingness to pay (WTP) is relatively high. A number of studies used non-market approach to value the municipal and industrial water uses mainly through estimating the economic cost of urban water scarcity based on optimization models or by analyzing the WTP to avoid shortage using CVM. Several empirical studies used market based approach and indicate that the municipal and industrial users are less sensitive to price. The municipal and industrial water demands therefore can be treated relatively inelastic with an elasticity value normally higher than –1 (Diaz et al., 1997) and in general falls between zero to -2. The main challenges in estimating the price-elasticity is block-rate schedule, dataset size, level of disaggregation and price specification (Young 2005).

An easy form and widely used technique to characterize the municipal and industrial water use demand curve is the 'point expansion method' using an observed price and water-use data along with a long-run constant price-elasticity. The demand curve is calibrated for a two parameter functional form by solving the resulting two identities. Assuming constant price elasticity during the time period t, the net benefit function for M&I uses is derived from an inverse demand function of water using the market price of the commodity. Such inverse demand function is used in few earlier works such as Ringler (2001) and Babel et al. (2005). The benefit function (Equation 3-2) is calculated as water use benefit minus water supply cost including cost of water treatment in monthly basis.

$$B_{j,t} = w_{0(j,t)} * P_0 * \left[\frac{1}{1+\alpha} * \left(\frac{w_{j,t}}{w_{0(j,t)}} \right)^{\alpha} + \left(0.743 - \frac{1}{1+\alpha} \right) \right] - w_{j,t} * wc_{j,t} \qquad (3\text{-}2)$$

Where, $B_{j,t}$ is the benefit from M&I sector at node j and time period t; $w_{o(j,t)}$ is the maximum normal monthly withdrawal at node j (in 10^6 m^3); P_o is the price of water at full use; $w_{(j,t)}$ is the actual water withdrawal at node j and time period t; e is the price elasticity of demand, α is the inverse of e; $w_{c(j,t)}$ is the cost of water supply at node j in time t.

For different w (actual water withdrawal) benefit can be calculated and then feed to Equation 3-1 which will finally give the benefit function.

3.2.2 Irrigation demand site

In general, market plays an insufficient role in case of irrigation water; developing countries are particular cases in point. Such situation demands special attention from the economists to value irrigation water using non-market valuation techniques (Young, 1996; Agudelo, 2001). Empirical estimation of the economic value of the irrigation water indicates the farmers' ability to pay for irrigation water (Young, 2005a). Agricultural water is therefore often valued using the crop-productivity related benefits at the local level or by considering the production related benefit at national level; even though recent studies show that the total benefit would be much larger when the indirect benefits from the water-induced farm and non-farm activities are accounted for (Hussain et al., 2007). Both the average and marginal values are used in performance evaluation of the irrigation water related projects. Several studies investigated the gross average value of irrigation water; however, a few of them (e.g. Booker and Colby, 1995; Agudelo and Hoekstra, 2001) found the point estimate of marginal value (not the marginal benefit function) of irrigation water.

Several non-market valuation methods including inductive (observation based) and deductive (using logical and mathematical rules) techniques are available to measure the value of irrigation water (inductive and deductive methods are mentioned in Table 2.3). In case of irrigation water valuation, inductive techniques principally include direct observation on water right market (used by e.g. Anderson, 1961 cited in Young, 2005a), land value method (proposed by the U.S. Water Resources Council), hedonic property value (used by e.g. Faux and Perry, 1999; Butsic and Netusil, 2007) and econometric valuation from primary (e.g. Turner et al., 2004) and secondary (e.g. Moore, 1999) data. Residual imputation method (RIM) is on the other hand frequently used a deductive technique and recently used by several researchers e.g. Agudelo and Hoekstra (2001), Speelman (2008; 2009) etc.

Residual imputation method accounts for the incremental contribution of each input in a production process. In the market with competitive equilibrium, when correct prices – equal to their marginal returns – are assigned to all input resources used in production process except one (water in this particular case), the remainder of total value of the product is imputed to the remaining or the residual input resource (Young, 1996; Agudelo, 2001). Assuming that the prices of the agricultural inputs are not distorted by subsidies, taxes etc, the total value of production can be divided into shares, in such a way that each resource is paid according to its marginal productivity and the total product is completely exhausted (Young, 1996). Following this principle the total value of production (TVP) equals the opportunity cost of all the inputs (Agudelo, 2001) as expressed in Equation 3-3a.

$$TVP = \sum VMP_i * Q_i + VMP_w * Q_w \qquad (3\text{-}3a)$$

Where *TVP* is the total value of the commodity produced; VMP_i is the value of marginal product of input *i;* Q_i shows the quantity of input, *i* used in production, *w* for irrigation water. From Equation 3-3a, VMP_w, the shadow price of water, can be obtained; it indicates the maximum amount the farmer could pay for irrigation water and still can cover the cost of production when the marginal value product of all inputs are considered at their market price. Therefore, Equation 3-3a can be rearranged and presented as Equation 3-3b to estimate the *VMP* of water:

$$VMP_w = \frac{TVP - \sum P_i * Q_i}{Q_w} \qquad (3\text{-}3b)$$

Where P_i is the price of input *i*.

Value derived from RIM coupled with water-crop production-function estimating the crop yield in relation with varying level of water-shortage form the basis to find the total and marginal benefit functions for irrigation water use. Using the concept of yield response to water stress is used in this study, which gives benefit at different water availability levels. Benefits obtained from different water availability levels are used to develop the total benefit function using Equation 3-1. It is worth noting that in general irrigation benefit is derived for the cropping season or year; however, in this research the benefits are extended for smaller time period, months by uniformly distributed the benefits over the irrigation season months.

Residual Imputation Method and its use for irrigation water valuation are discussed more in depth in Chapter 5 under Section 5.2.2.

3.2.3 Hydropower

Power generation in a certain time period from a hydropower plant is a function of its installed capacity, flow through the power plant, the productive hydraulic head, and its production efficiency. The generated electrical energy, P (kW) is approximated by Equation 3-4.

$$P(kW) = 9.8\eta QH \qquad (3\text{-}4)$$

Where, Q is the discharged through the power-plant in cubic meters per second, H is the net (or effective) hydraulic head on the turbines in meters, η is the overall (turbine-generator) efficiency. Customarily, the capability of a power-plant to produce energy is expressed by the energy rate function (*erf*), which calculates the amount of energy (in kilowatt hours) generated by the plant per unit volume of water released through its turbines (in cubic meters) during a unit period of time (one hour), which is expressed in Equation 3-5.

$$erf\left(kWh/m^3\right) = \frac{1}{367}\eta H \qquad (3\text{-}5)$$

After multiplication of *erf* with the energy price (US\$/kWh) the value of water (US\$/m^3) is obtained.

Detailed method of valuation of water used in hydropower with its application is discussed in Chapter 10 under Section 10.1.

3.2.4 Reservoir recreation and fishery

For an already existed reservoir (meaning that its size was determined by other water uses) the recreation activity is assumed to be a function of reservoir water level. In this manner, the total benefit function for reservoir recreation and fishery is assumed to be a hyperbolic tangent function (mentioned in Equation 3-6) as stated in Diaz et al 1997.

$$B_{j,t} = a\left[tanh\left(b\overline{S_{j,t}} - c\right) + 1\right] \qquad (3\text{-}6)$$

Where, $B_{j,t}$ is the recreation benefit from reservoir j at time period t, $\overline{S_{j,t}}$ is the average storage during time period t for the j reservoir, and a, b, c are the coefficients of the model.

Reservoir activities is assumed limited between a maximum and minimum reservoir level. An example of hyperbolic benefit function is depicted in Figure 3.2.

The hyperbolic benefit function is asymptotic to the lowest and highest reservoir recreation levels. In order to establish the benefit function the lowest and highest recreation storage level is needed to be defined first. Afterwards the coefficients, *a, b,* and *c* can be set with the help of pre-established maximum total benefit value. Parameter *a* is estimated as the half of the maximum benefit, *b* is the small scaling coefficient (often considered as 0.001) that controls the slope and *c* is the initially estimated average storage multiplied by *b*. Finally the function needs a calibration.

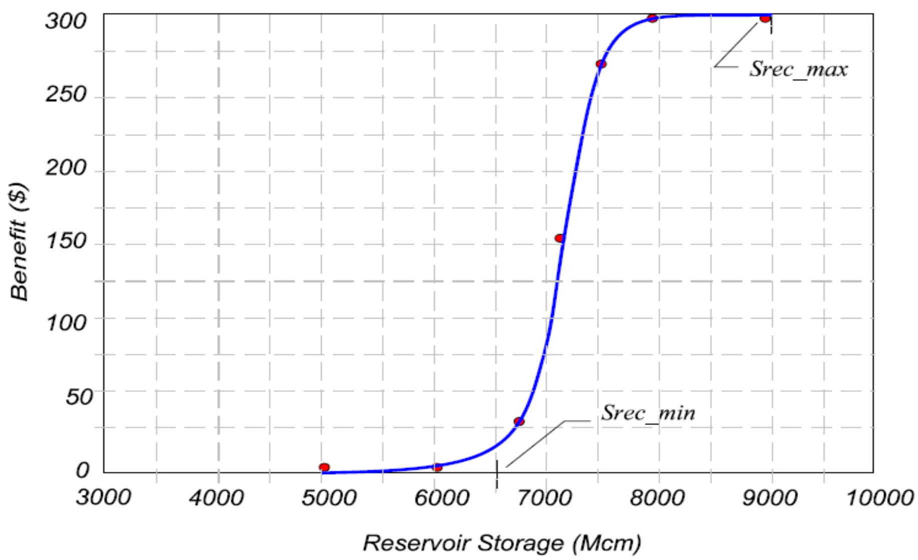

Figure 3.2 A representative fitted reservoir recreation total benefit curve
Source: Diaz et al., 1997

Method of valuation of water used in reservoir recreation with its application is discussed in Chapter 10 under Section 10.3.

3.2.5 River recreation and instream flow direct uses

Since the instream recreational activities are non-marketed goods, unique economic valuation approaches such as travel cost method (TCM) analysis or contingent valuation (CV) are required and widely used. Daubert and Young (1981) and Duffield et al. (1992) identified quadratic relation of total recreational benefits for instream flow which shows an increasing benefit at the beginning then it stabilizes and then decreases with further increase on flow rate. For example, at low flow rate the rapids are not a challenge for the whitewater boaters, floating quality increases with further increase in flow rate, but at very high flow rate the rapids become washed out. Same principle is applied for all instream flow recreation activities.

The analytical form of the total and marginal benefit function for instream flow recreational activities adopted in this study is followed as Diaz et al. (1997). The gross benefit function is represented as a quadratic function that results a linear marginal benefit function.

Using the same analytical approach of instream flow recreation, the instream water direct uses, such as capture fishery and navigation which are of especial interest in the poor socio-economic settings, a quadratic function is established for estimating the total benefit. In such cases, incomes of the fishermen and boatmen are treated as the overall benefit on the instream water use and the income variation against the flow fluctuation can act as a basis for developing this function.

The functional form of the total benefit function for instream water recreation and instream water direct uses are again same as Equation 3-1.

Method of valuation of instream water direct uses such as river fishery and navigation with its application are discussed more in depth in Chapter 6 under Section 6.2 and Section 6.3.

3.3 Consideration of environmental flow requirements

Several methods to assess the EF requirements are available as mentioned in Section 2.3.4. The methods differ in scope of application and data requirements. However, maintaining the natural variability of flow while estimating EF is the prime concern. Since the study deals with hydrological data very closely, application of hydrological methods for assessing EF is a good choice. Hydrological methods are simple, less resource- and data-intensive, rapid and widely used. These methods correspond to standard setting problems (as classified by Stalnaker et al., 1995). In this category, the methods use only historical flow data, usually in the form of naturalized, historical monthly or daily flow records. Prominent hydrological methods include the Tennant method (Tennant, 1976), Flow Duration Curve method, Constant Yield method (Jowett, 1997; Karim et al., 1986) and the Range of Variability Approach (Richter et al., 1997).

Three different hydrologic methods namely, Tennant method, Flow Duration Curve (FDC) method and the targeted RVA (Range of Variability Approach) boundaries using IHA (Indicators of Hydrologic Alteration) software are used to estimate EF requirements for the case study rivers.

Tennant method deals with mean annual flow (MAF). In this case, mean annual flow is estimated based on daily or monthly flow data. Environmental flow is fixed for different season as percentage of MAF as suggested by Tennant. In FDC method, monthly FDC is developed using mean daily flow of the concern downstream location and EF is fixed from the FDC as a certain percentage of exceedence probability. In RVA method, mean daily flow data for at least 20 years is required. Using IHA software, 32 RVA parameters are estimated. In the base case, +/-1 SD (standard deviation) is used as RVA target. Afterwards, obtained results from the three methods are analyzed and a certain flow is fixed as EF (often as lower limit) for monthly basis. Detailed method of EF estimation is given under Section 2.3.4.

3.4 Optimization model for water allocation

The river is schematized as a node-link network representing the spatial relation between various off- and in-stream demands in the basin in the optimization model as represented in Figure 3.3. Nodes represent the demand sites and links represent the linkage between river reaches. Flow balances are calculated for each node for each time period endogenously within the model, and flow transport in the basin is calculated based on the spatial linkages in the river basin network. The model incorporates both offstream and instream water uses. Water demands are determined separately. Instream water requirement is assessed by using hydrologic methods. Water supplies are determined through the hydrologic simulation. Water supply and demand are balanced based on the objective of maximizing economic benefits to water use. Time horizon is considered one year in a monthly step. Consumer surplus for each water use is maximized in the optimization module of the model from the pre-established marginal benefit functions.

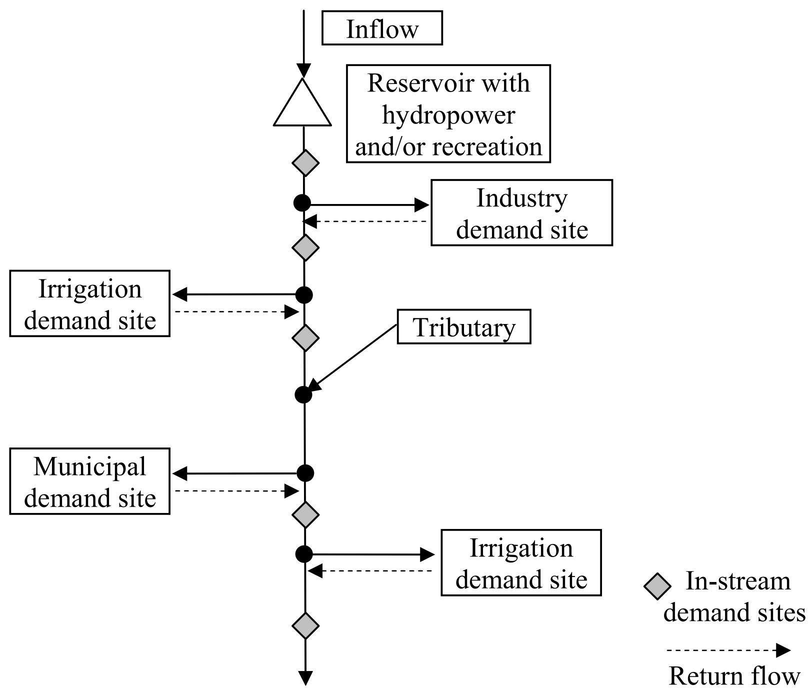

Figure 3.3 River basin node-link network

3.4.1 Model formulation

Water allocation throughout a system and for a time period or planning horizon (e.g. one year) is based on a global objective; to maximize the overall economic benefit from all off- and in-stream water uses under a specified set of constraints. The individual benefit functions are developed beforehand, what remains is to combine those individual benefit functions into a total benefit function TB that reflects all water uses in the basin and all time periods in the optimization horizon. The overall objective is to maximize the total benefit function TB as presented in Equation 3-7.

$$Maximize\,TB = \sum_{t=1}^{nt} \sum_{j=1}^{nj} B_t^j \qquad (3\text{-}7)$$

Where *nj* is the number of water uses generating revenue in the basin and *nt* is the number of time periods (optimization horizon). The equation considers all possible benefits (*B*) from water uses. B is a function of flow for all uses, where allocation of the available flow to a specific user and at a specific time is the decision variable. Hence, the decision variables can be expressed mathematically in Equation 3-8,

$$Q = \begin{bmatrix} Q_1^1 Q_2^1 \ldots Q_{nt}^1 \\ Q_1^2 Q_2^2 \ldots Q_{nt}^2 \\ Q_1^3 Q_2^3 \ldots Q_{nt}^3 \\ \vdots \\ Q_1^{nj} Q_2^{nj} \ldots Q_{nt}^{nj} \end{bmatrix} \tag{3-8}$$

Where, nt is the number of time periods and nj is the number of users and Q is the flow.

The problem of maximizing the objective function is subjected to physical, operational and institutional constraints as listed in Equation 3-9(a) – (h). The constraints are:

– Hydrologic flow balance at any node, j at any time period t

$$Flow_{d/s} = Flow_{u/s} + local\ drainage + return\ flow - withdrawals - losses \tag{3-9a}$$

– Constraints for reservoir

Conservation of mass

$$S_{t+1}^j = S_t^j + I_t^j + PP_t^j - R_t^j - EV_t^j - L_t^j; \tag{3-9b}$$

Where, S_t^j and S_{t+1}^j represent reservoir storages at the beginning of time periods t and $t+1$ in volume units, respectively. $I_t^j, PP_t^j, R_t^j, EV_t^j$ & L_t^j are inflow, precipitation over the reservoir, reservoir release, evaporation, and water leakage through dam respectively from reservoir j

Useable storage capacity

$$S_i \leq S_{max} - S_{dead} \tag{3-9c}$$

Average elevation

$$h_t^j = \left(k_t^{initial} + k_t^{final}\right) * 0.5 \tag{3-9d}$$

Here $k_t^{initial}$ & k_t^{final} are the initial and final fore-bay elevations for the time period t associated with the power station installed with reservoir j respectively.

Upper limit on power production for the plants

$$\rho g(k_t^j - T_t^j - H^j) * Q_t^j * \eta^j \leq P_{cap} \tag{3-9e}$$

Where, P_{cap} is the maximum power production capacity of power plant j; ρ and g represent their conventional meanings of water density and acceleration due to gravity respectively. The head for power generation is given as the difference between the fore bay elevation k and the tail-water elevation T at time interval t and for plant j; H^j is head loss due to friction in the tunnel and the penstock. Q is the discharge through penstock j for time interval t and η is the overall efficiency of the plant j.

Operation rule curve

$$Lower\ limit \leq k_t^j \leq Upper\ limit \tag{3-9f}$$

– Water supply to a user

$$0 \leq Q_t^u \leq demand^{max} \tag{3-9g}$$

Where, Q is the allocated flow to user, u in time period t.

– minimum instream flow demand,

$$EF_t \geq EF^{min} \tag{3-9h}$$

Where, EF is the environmental flow or any other instream flow demand at any instream point and at a time period t.

Generalized hydro-economic model, Aquarius is used to solve the optimization model for water allocation.

3.4.2 AQUARIUS – a generalized hydro-economic model

Diaz et al. (1997) introduced a computer-based model "Aquarius" devoted to the spatial and temporal allocation of water among uses in a river basin. The model finds the economic efficiency of the system that entails a reallocation of the stream flows until the net marginal return in all water uses is equal. All the water uses are represented by a demand curve i.e. the marginal benefit function either by exponential, linear or constant type. This modeling platform is used to solve the optimization problem of the case study basins.

Aquarius supports modeling of both groundwater and surface water sources; several water control structures, e.g. reservoir, diversion, junctions etc.; two types of conveyance structures (natural river reach or man-made canals/pipelines); seven different water uses namely: irrigation, hydropower, instream flow protection, instream recreation, reservoir recreation, municipal and industrial supply and flood control areas.

The use of demand functions involving exponential, linear or constant type requires a complex non-linear objective function. However, the solution technique uses a special case of the general nonlinear programming problem by reducing the objective function into quadratic form using Taylor Series expansion and all the constraints are linear. Optimization problem is solved using sequential quadratic programming (SQP) starting with an initial feasible solution until the quadratic problem reaches the optimal solution that involves with a systematic examination of the viability of reallocating the marginally valuable unused or storage water in favor of alternative uses. An efficient quadratic programming (QP) code is a basic requirement for the success of the proposed solution method. The routine 'QPTHOR', based on the general differential algorithm is used in Aquarius model. A succession of the approximations is performed until the solution of the quadratic programming problem reaches the optimal solution, which is when successive optimal values do not differ by more than the stipulated tolerance limit, or when the maximum limit on the number of iterations is reached. Figure 3.4 illustrates the sequential procedure of successively solving quadratic programming problem, known as SQP.

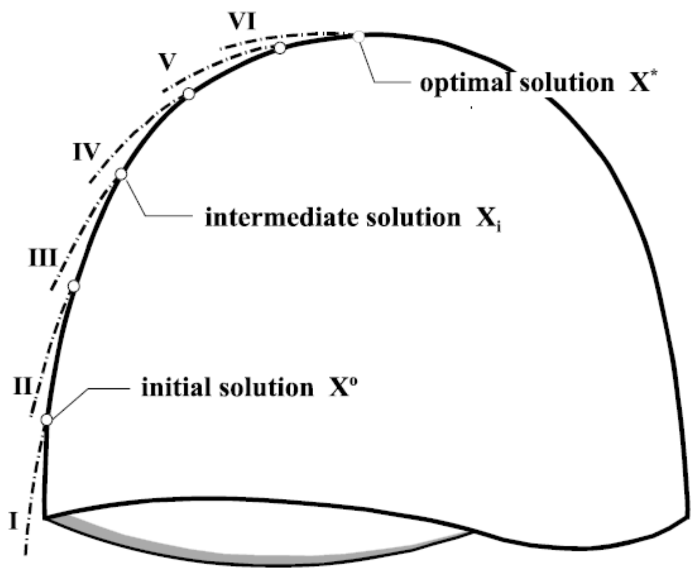

Figure 3.4 Sequential maximization of a concave objective function by Sequential Quadratic Programming
Source: Diaz et al, 1997

The optimization model is coded using an object-oriented programming (OOP) language C++. Water systems are ideal candidates for modeling under an OOP framework, where each water system component is an object in the programming environment. The model runs on a personal computer under the Microsoft Windows operating system. By using the inherent capability of the graphical presentation of the OOP, the 'Network Worksheet Screen (NWS)' gives access to users' interaction with the model that represents the water system of interest. Each water system component – a node or link – in the NWS is pictorially indicated by an icon which can be used from the menu bar by dragging and dropping. Components can be removed or relocated any where in the NWS. Once the 'nodes' are placed, they are connected through 'links' or the conveyance structures.

Two prime sets of data – physical and economic – are given as input to the model. The physical data comprise the information associated with the water demand, return flow, reservoir characteristics, power plant efficiency, operational characteristics and the dimensions of the system components. Economic data involves with mainly the demand functions or the marginal benefit functions of the various water uses. Currently available version (version 05) of the 'Aquarius' simulates the water allocation in a monthly time step; therefore the input data are organized in monthly basis.

3.5 Model application

The developed water allocation optimization model is applied to the Teesta River from Bangladesh and to the Konto River from Indonesia to allocate water optimally and subsequently to estimate the optimal benefit from the water uses in the basins. Two river basins are chosen from two countries having different set of development, management and water uses.

Teesta in Bangladesh is a transboundary river shared with India. The portion falls inside Bangladesh is the downstream part of the river and only this portion has been considered for this study. No reservoir or any other hydraulic structure exists on the study site of Teesta except one irrigation purpose barrage. Irrigation water withdrawal is the only offstream use and capture fishery and navigation are the instream water direct uses. On the other hand, Konto in Indonesia is a sub-basin of a large river system, Brantas. Konto has one reservoir and a series of hydropower project. Water used in one hydropower plant is again used by another plant and finally the water does not flow back to the main course of Konto rather the water is used for irrigation purpose. Stepwise value addition to a unit of water released from the reservoir is the main feature of the Konto. Direct instream uses are reservoir fishery and recreation. Offstream water uses are economically far more beneficial than instream water direct uses for both Teesta and Konto.

Detailed description of the Teesta and the Konto are given in Chapters 4 and 9 respectively.

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PART-II

Chapter 4: Teesta River: study site in Bangladesh
Chapter 5: Benefit function of offstream water use in the Teesta River
Chapter 6: Benefit functions of instream water uses in the Teesta River
Chapter 7: Environmental flow for the Teesta River
Chapter 8: Optimal water allocation in the Teesta River

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4 TEESTA RIVER: STUDY SITE IN BANGLADESH

4.1 The Teesta River, Bangladesh

Teesta, the forth major river in terms of flow in Bangladesh is chosen as the case study river to apply the water allocation model. The Teesta originated from the glaciers in the Indian state Sikkim at an elevation of 7,128 m in the Eastern Himalayas. Flowing for almost the entire length of the state, the emerald-colored Teesta then forms the boundary between West Bengal and Sikkim (states of India) before entering into Bangladesh at Chatnai, Nilphamari district. The river finally meets with the Jamuna River in Bangladesh. Total length of the Teesta is about 315 km of which about 113 km falls inside Bangladesh (Bari and Marchand, 2006).

Teesta is the main source of water in the northwestern drought-prone but agriculturally high potential region of Bangladesh. Figure 4.1 shows the location map of the Teesta River in Bangladesh and the Teesta Irrigation Project (TIP) boundary. The river flow has been regulated since 1987 when India constructed an irrigation barrage at Gazaldoba. Another barrage with same purpose was commissioned at Dalia-Doani inside Bangladesh in 1990 to supply water to the TIP. Daily flow is measured above the TIP barrage by the Bangladesh Water Development Board (BWDB). Downstream of the barrage and before the confluence of Teesta with Jamuna, there is another flow gauge station at Kaunia Railway Bridge point (Figure 4.1). The section of Teesta River between the TIP barrage at the upstream to and Kaunia at the downstream, which is about 70 km in length is considered as the study site. The river reach crosses three administrative districts of the country, namely: Rangpur, Nilphamari and Lalmonir Hat. For administrative purposes, Bangladesh is divided into districts, Upazila (sub-districts) and unions while the latter one is the smallest administrative unit. To fix the lateral boundary of the study site one riparian union is considered along the bank and 26 such riparian unions are found at the both banks of Teesta in the study site reach.

The Teesta is a sandy braided river with steep slope, exhibiting high seasonal flow variability and cause inundation of floodplains in monsoons and very low flow conditions in the dry season. Based on the last forty years (1967 – 2006) mean daily flow at Kaunia as obtained from BWDB, mean annual discharge at Kaunia is 863 m^3/s. Mean annual discharge has fallen to 831 m^3/s in the post barrage period (1991-2006) from 885 m^3/s in the pre-barrage (1967 – 1990) period. Figure 4.2 presents the mean monthly flow at Kaunia for the pre- and post-barrage periods. It is evident from the Figure 4.2 that the mean monthly flow has been reduced in the post-barrage period for all months except August. The figure also shows the flow variation within the year. Teesta flow can be divided into three seasons, namely: wet season (June - September), dry season (December – March) and intermediate flow season (April, May, October and November). Rainfall is mostly concentrated in the wet (monsoon) season. Average annual rainfall in the Teesta region is about 2,400 mm/yr, of which more than 70% occurs in wet season four months and more than 90% falls in between May to October.

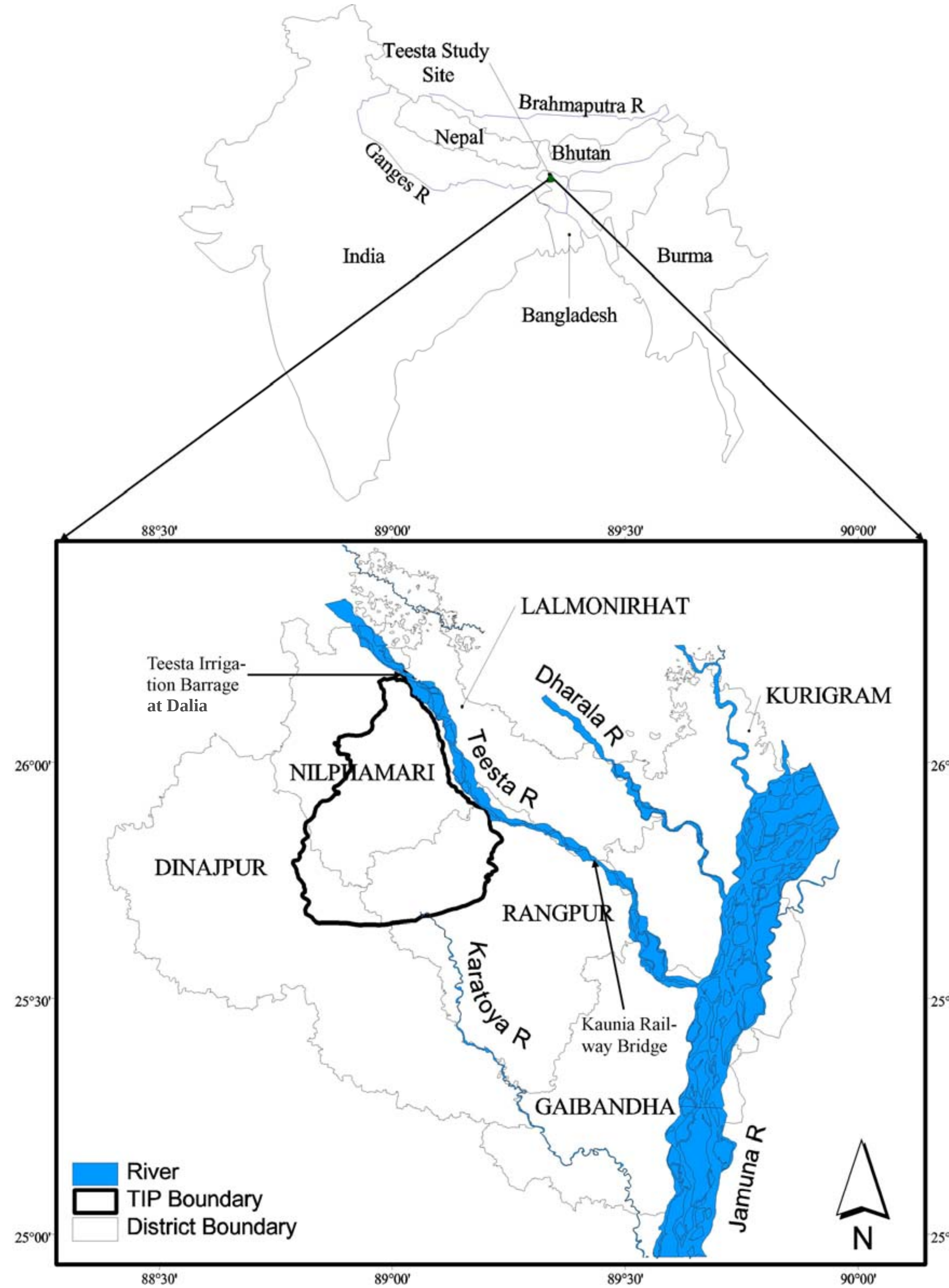

Figure 4.1 Teesta River and Teesta Irrigation Project in Bangladesh

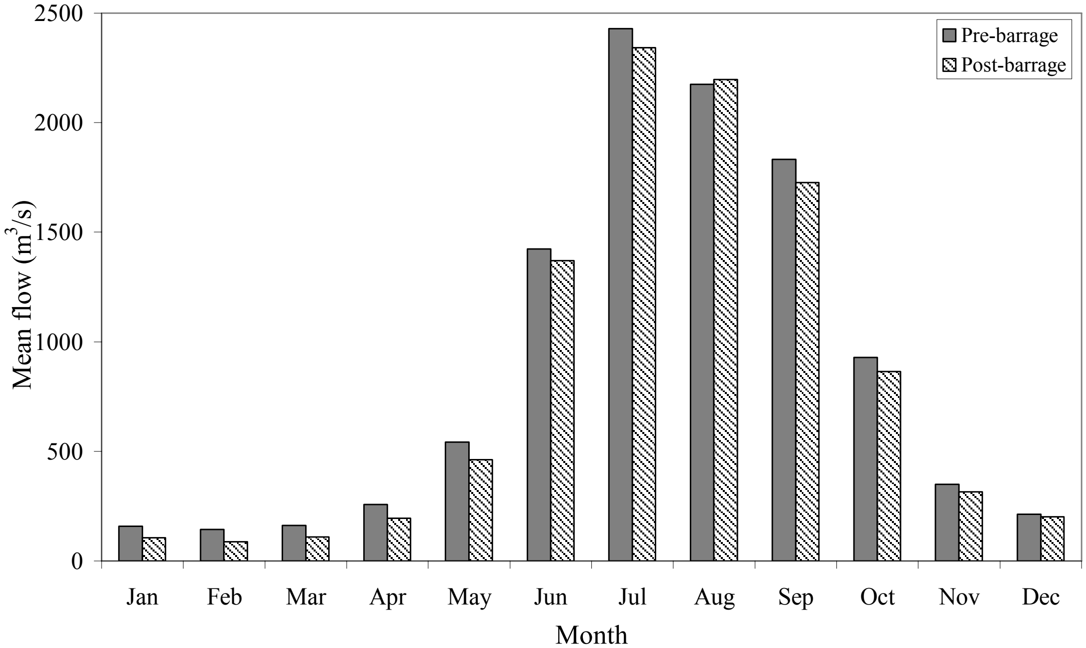

Figure 4.2 Mean monthly flow (MMF) for the pre-barrage (1967 – 1990) and post-barrage period (1991 – 2006) at Kaunia Railway bridge on the Teesta river

4.2 Socio-economic condition

Overall socio-economic condition of the study area (the riparian unions) is very poor. Agriculture is central to the economy of the study site and the main occupations of the inhabitants are farming, labor selling, fishing and rickshaw pulling. Total population of the 26 riparian unions at the study site is 555,302 with average literacy rate of 34.4%. Out of total 125,415 households in the riparian unions, number of households involved in agriculture, forestry and livestock works are 53,655 (43%), in agriculture labor selling are 40,817 (32.5%), in fishery are 920 (0.7%) and in transport related jobs are 2,028 (1.6%). Only 14,803 (11.8%) households have access to sanitary latrine and 10,054 (8%) households have the electricity connection. However, 112,479 (90%) households use groundwater for their drinking purpose. The adjacent areas of the river banks are completely rural with poor accessibility due to less developed transportation system. No data and information related to the livelihood activities and their life and income pattern with river flow of the instream water users as well as monthly fish production is directly available from any source. Salient features of the socio-economic condition of the study site are reported in Table 4.1.

4.3 Water uses from the Teesta River

The main water use from the Teesta is irrigation use. In addition, Teesta is important for fishery and small scale navigation. The river flow is also necessary to maintain and safeguard proper functioning of the river including several subsistence uses such as subsistence irrigation, washing and bathing of riparian people and livestock etc. However, in-stream water requirements have not been assessed the instream flow requirements set forth in different management plans until now are based on some crude judgment (Bari and Marchand, 2006).

Table 4.1 Socio-economic conditions of the Teesta study site based on selected criteria

District	Upazila	Riparian Union	Total population	Literacy rate	Total HH*	HH with tube well	HH with sanitary latrine	HH with electricity	HH Agri/forestry livestock	HH fishery	HH agri labor	HH transport	HH service	HH other works*
Rangpur	Gangachara	Alam Biditar	30,983	28.19	7,820	6,972	200	539	3,189	49	3,049	62	217	1,254
		Gangachara	33,197	45.99	7,445	6,684	1,583	1,750	2,866	52	2,111	284	494	1,638
		Gajaghanta	28,018	37.07	6,244	5,809	475	1,109	2,819	21	1,478	230	282	1,414
		Kolkanda	24,415	32.61	5,428	4,642	813	728	2,292	82	2,084	68	166	736
		Lakshimari	17,379	30.66	4,095	3,708	206	238	1,995	31	1,309	94	100	566
		Nohali	21,428	25.04	5,276	4,964	188	173	2,516	75	1,999	35	93	558
		Marania	25,176	20.78	5,869	5,415	439	500	2,273	6	1,135	51	116	2,288
	Kaunia	K. Bala Para	30,740	42.50	7,014	6,339	2,316	1,564	2,687	93	1,574	174	552	1,934
Nilphamari	Dimla	Jhuna-Chapani	25,146	28.6	5,529	4,627	358	509	1,777	32	2,500	40	144	1,036
		Khali-Chapani	24,549	34.69	5,301	3,725	244	236	2,177	51	1,730	44	177	1,122
	Jaldhaka	Kaimari	34,824	29.7	8,010	7,140	554	322	3,089	37	3,481	172	151	1,080
		Saulmari	20,245	27.52	4,573	4,008	356	391	2,299	9	1,657	25	108	475
		Daoabari	10,025	28.81	2,169	1,913	19	15	1,011	8	789	47	39	275
Lalmonir Hat	Aditmari	Mohiskocha	24,493	33.35	5,290	4,881	115	302	2,454	6	1,484	73	159	1,114
		Palashi	28,177	42.30	6,042	5,666	138	240	2,511	57	2,083	162	125	1,104
	Hatibanda	Doabari	17,475	31.38	3,866	3,573	189	78	2,326	11	979	54	68	428
		Goddimari	16,209	38.84	3,605	2,988	346	137	1,369	84	1,147	99	201	705
		Patikapara	10,528	30.79	2,464	2,087	39	56	1,367	9	654	21	65	348
		Sindurna	11,520	36.37	2,450	2,333	672	72	917	7	746	93	122	565
	Kaliganj	Bhotemari	20,735	28.40	4,929	4,778	525	57	2,217	25	1,661	17	116	893
		Kakina	28,780	37.84	5,947	5,542	1,303	157	2,463	92	1,928	38	205	1,221
	LH Sadar	Gokunda	29,564	54.41	6,454	5,843	2,163	648	2,323	42	1,938	110	324	1,717
		Khuniagachh	25,717	28.35	5,917	5,251	368	125	2,561	25	2,211	31	166	923
		Rajpur	15,979	52.75	3,678	3,591	1,194	108	2,157	16	1,144	4	64	293
Total			555,302	34.45	125,415	112,479	14,803	10,054	53,655	920	40,871	2,028	4,254	23,687
(% of total HH)						89.7%	11.8%	8.0%	42.8%	0.7%	32.6%	1.6%	3.4%	18.9%

Source: BBS (2005); *HH=House-hold; other works include non agriculture labor, hand loom, industry, business, hawker, construction, religious, remittance work

Along both the banks of the river, no major domestic and industrial abstractions of water from the river came across the documents from different organizations. The adjacent area is completely rural with poor socio-economic condition where a number of people are engaged in fishing and boating as their prime livelihoods. Irrigation at the off-stream side and river fishery and small scale navigation at the in-stream side are three major direct uses of water from the Teesta which have been considered for the study and water allocation problem.

4.4 Teesta barrage and irrigation project

Due to the flat topography of the country, canal irrigation system does not possess significant potentiality in Bangladesh. However, BWDB has 376 small and large-scale surface water irrigation projects and the Teesta Irrigation Project is the largest. The idea of irrigation from the Teesta was first conceived in British regime (1935); however, the barrage construction was started in Eighty's and commissioned on August 1990. It is located on Teesta River at Duani in Hatibanda Upazila of Lalmonir Hat district. The project has a design capacity to supply water to 540,486 ha of agricultural land through one canal head regulator having discharge capacity of 283 m^3/s. The project command area covers seven administrative districts in the north-west Bangladesh. The main canal systems of the TIP consist of four main canals i) Teesta main canal, ii) Dinajpur secondary major canal, iii) Rangpur secondary major canal and iv) Bogra secondary major canal. Length of the Teesta main canal, total secondary major canal, secondary canal and tertiary canal are 33.67 km., 74.85 km, 224.91 km and 356.53 km respectively. Natural river system serves the drainage of the project and ultimately the return flow drains to Jamuna River that helps Teesta river water free from intensive agricultural pollution.

To gain early benefits, the project was planned to be implemented in phases, viz. Phase-I and Phase-II. However, the only implemented phase, Phase-I of the project has a gross command area of 154,250 ha and net irrigable area of 111,732 ha (BWDB, 2005). Rice is by far the most important crop grown all the year round. Three different varieties of rice are grown in the TIP area (i) *Aman*, grown in mid August to mid December, (ii) *Boro*, grown in mid December to mid April, (iii) *Aus*, cultivated from May to August. Mostly being high yielding varieties (HYV), these rice varieties are low-land transplanted type and require irrigation either fully or partially in their life cycle. *Aman* and *Aus* need supplemental irrigation at their final and initial stages of growth respectively whereas *Boro* has the highest yielding potential and requires continuous irrigation during its growth period. Double-cropped areas are predominant accounting for 82% while 18% areas are triple cropped which makes the total cropping intensity of TIP is 218% (BWDB, 2005). The whole project is at the right side of the river and fed through only one diversion.

Primary objective of TIP was to provide supplemental irrigation to post-monsoon *Aman* field; however, currently it supplies water for irrigation in the entire dry season based on the flow in the river at the barrage (BWDB, 2008). Present agricultural practice has widely changed from that conceived during project planning and farmers are now more interested to grow HYV *Boro* rice, which demands huge irrigation supply. Since the available water at the barrage does not often meet the irrigation demands in dry months, farmers extract groundwater for irrigation. Groundwater potential and use in the TIP area is quite considerable. In a study, Wahid (2003) reported 51,094 shallow tube wells (STW) and 639 deep tube wells (DTW) in the TIP area in 2000. Wahid (2003) also calculated the average annual abstraction over the area to be 641 mm, actual recharge 682 mm and maximum allowable abstraction 624 mm.

4.5 Water management of the Teesta

Teesta is flowing across the region having very high potential for agricultural production and the TIP aims to accelerate the agricultural production up to its full potentiality by supplying irrigation water. At the same time the project also aims socio-economic enhancement by introducing multiple development program viz. fisheries, duck culture, grass cultivation, afforestation etc. Hence, multiple government organizations are involved to attain the project objectives. The involved organizations are Bangladesh Water Development Board (BWDB), Directorate of Agriculture Extension (DAE), Directorate of Fishery, Directorate of Livestock, and Directorate of Forestry. However, BWDB is solely responsible for managing the water resources that includes diversion and distribution of irrigation water, maintenance of river and irrigation canals and keeping all the related data and information records.

Bangladesh Water Development Board works under the Ministry of Water Resources, Government of Bangladesh. BWDB is responsible for construction of dams, barrages, embankments, drainage systems, irrigation canals, as well as it negotiates with upper riparian countries for the management of the water of common rivers. The board has a chairman and five members. BWDB has five wings, namely: administration, planning, finance, implementation, Operation & Maintenance (O&M). O&M wing is responsible for operation and maintenance of the existing large project (area over 5,000 ha). Teesta irrigation project is run under O&M wing of BWDB. A project office of BWDB is situated close to the barrage for operation and maintenance of the barrage.

4.6 Data and information collection

4.6.1 Hydrological data

Daily average discharges for both the stations (Dalia and Kaunia) within the study site river reach were collected from BWDB database. Data on flow at Dalia was available for the period of 1986 – 2006 and for Kaunia the data was available for a longer period of 1967 – 2006. The data is processed as mean monthly flow and are reported in Appendix A, Tables A.1 and A.2. The flow data is used for estimating the environmental flow requirements and in hydrological simulation of the water allocation model.

4.6.2 Irrigation and crop production

Irrigation and crop production related data along with rainfall information were collected from BWDB database, TIP project evaluation report (BWDB, 2005) published by BWDB planning section and from Institute of Water Modeling (IWM). Prices of inputs and outputs of agricultural production are based on market price as of 2008 at or near TIP. All these data is reported in Chapter 5.

4.6.3 Instream water direct uses

Instream water direct uses for the Teesta are fisheries and small scale navigation. However, data and information related to the water uses and users are not available from any source. Towards finding the instream water direct use benefits, estimating total number of such water users are the primary concern. In line with this concern, the lateral boundary of the study site is considered as one riparian union at both the banks of the river reach. The underlying assumption in such consideration is that the Teesta river instream water users i.e. the fishermen and boatmen live only in the riparian unions either of the sides of Teesta.

Instream water use related benefits are revealed for the study using a primary survey conducted on the fishermen and boatmen group in the riparian unions. Out of 26, 11 riparian unions are selected arbitrarily for the primary survey. The unions are Gangachara, Lakshimari, Marania and Kaunia Bala Para from Rangpur district, Kaimari from Nilphamari district and Palashi, Bhotemari, Kakina, Gokunda, Khuniagachh and Rajpur from Lalmonir Hat district. Location of the riparian unions under primary survey is shown in Figure 4.3. Detailed discussion on and outcomes from the primary survey are reported in Chapter 6 under Sections 6.2 and 6.3.

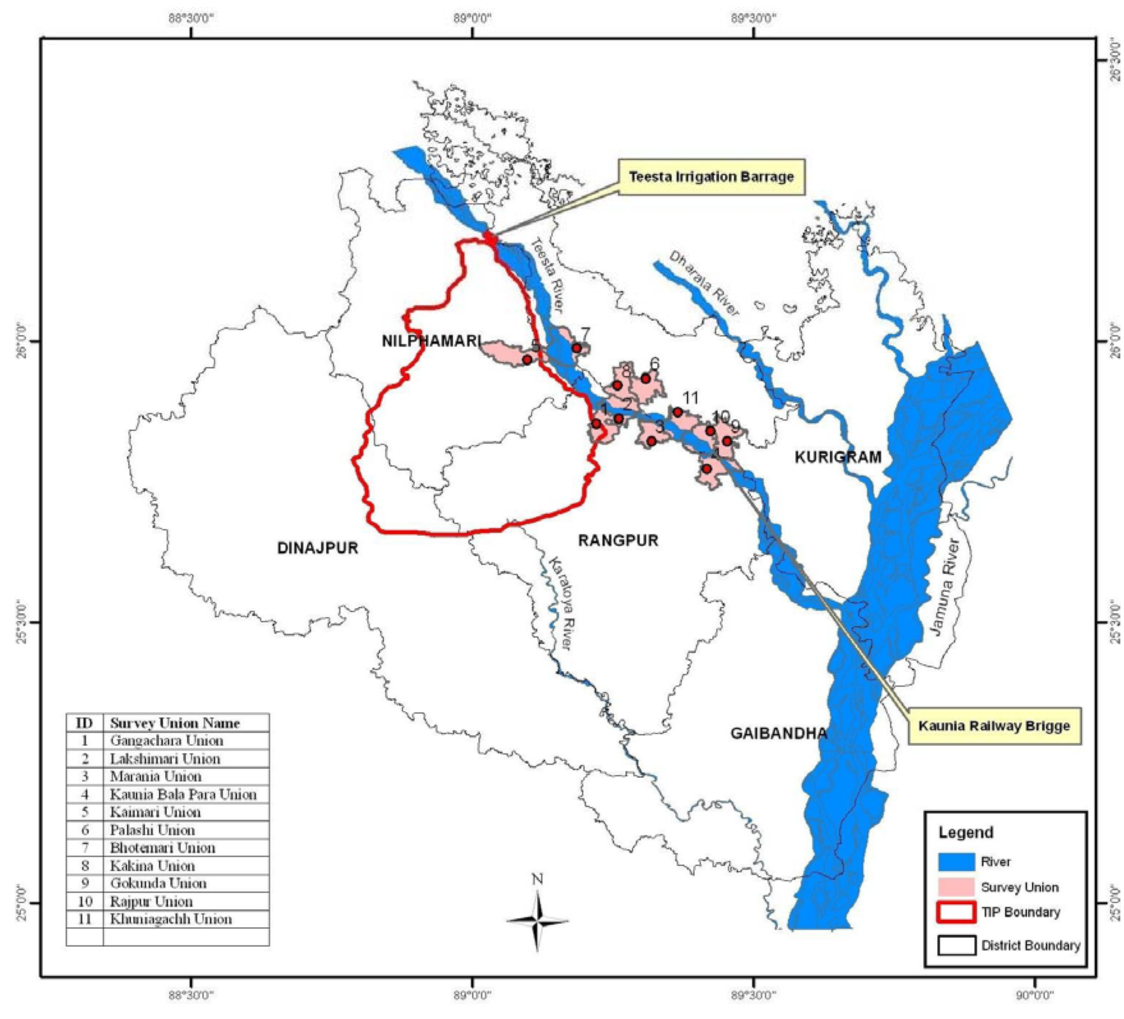

Figure 4.3 Study site and location of riparian unions under primary survey

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5 BENEFIT FUNCTION OF OFFSTREAM WATER USE IN THE TEESTA RIVER

Water uses from the Teesta are already discussed in Chapter 4. The main offstream use of the Teesta water is for irrigation purpose in the Teesta Irrigation Project. This chapter presents the estimation of the total and marginal benefit function of the irrigation water use from the Teesta. A brief discussion of agriculture, irrigation and irrigation water pricing system in Bangladesh and particularly at Teesta Irrigation Project is provided at the beginning of the chapter.

5.1 Agriculture and irrigation in Bangladesh – a brief overview

5.1.1 Agricultural practices

Agriculture is the most important economic sector in Bangladesh. It accounts for about 22% of the overall GDP and provides 51% of the total employment for the country (BBS, 2005). The country grows a wide variety of crops and those are classified into two major groups according to the seasons in which they are grown, namely: *Kharif* (further sub-divided into *Kharif*-I from mid March to mid July and *Kharif*-II from mid July to mid October) and *Rabi* (mid October to mid March). *Kharif* season spreads over spring up to late summer whereas *Rabi* is from early winter to early spring. Rice stands as the main crop among more than 80 crops grown in the country (Year book of Agricultural Statistics of Bangladesh, 2005). Different varieties of rice grow both in *Kharif* and *Rabi* season. Being the main crop, rice dominates the cropping patterns; however, cropping pattern also depends largely on land type, soil characteristics, and water availability. Table 5.1 shows the general cropping pattern of the country for various seasons.

Table 5.1 General cropping pattern in Bangladesh

Agriculture condition	**Cropping Season**		
	Rabi	***Kharif*-I**	***Kharif*-II**
Rain fed	Wheat/ Potato/ Pulses/ Oilseeds/ Sugarcane	*Boro* rice/ *Aus* rice/ Jute	Fallow
Irrigated	*Boro* rice/ Wheat/ Potato/ Tobacco/ Vegetables	*Aus* rice/ Fallow	*Aman* rice/ Fallow

Source: Banglapedia, National Encyclopedia of Bangladesh, 2009 (online).

5.1.2 Rainfall and irrigation

Bangladesh is endowed with a high rainfall of annual 2,666 mm in average (FAO, Aquastat, 2009); however, about 95% of the rainfall is concentrated in the monsoon during May to October, leaving the winter months i.e. November to March dry. Therefore, irrigation is a prerequisite for obtaining stable high yields especially for *Rabi* crops. Supplemental irrigation is also needed in the event of water shortage for the *Kharif* crops. The irrigated land area of Bangladesh was 5.03 million ha in 2004-2005 (BBS, 2005) and the agricultural water withdrawal was 76,400 Mm^3 in 2000 (Aquastat, 2009). Due to its flat topography, Bangladesh does not have a good potential of canal irrigation. Groundwater irrigation using tube well (both shallow and deep) are therefore widely used. Teesta irrigation project is the largest surface water irrigation project in the country; however, farmers use groundwater in dry season when supply from the river water does not satisfy the demand, which has already been mentioned in Chapter 4.

Since rainfall is very low in the dry season, *Boro* needs almost a full time irrigation; however, *Boro* yields the most stable and the highest. Net irrigation requirement for *Boro* from experimental field study is about 620 – 700 mm from transplanting to harvest whereas an extra about 240 mm of water is required for seed bed and land preparation (Karim et al., 1996), even though in the real cases, water requirement for land preparation might be higher. Supplementary irrigation is required for *Aman*. Depending on location and severity of water shortage, *Aman* needs 80 – 400 mm of irrigation (Karim et al., 1990). *Aus* needs irrigation at its early stage in particular for the north-west region of the country. Karim and Akhand (1982) reported 195 mm irrigation requirement for *Aus* rice at and around the north-west part of Bangladesh.

5.1.3 Irrigation water pricing

According to 'the East Pakistan irrigation water rate ordinance', formulated in 1963 and promulgated on 1966, the water rates were fixed at 10% of increased benefit of crop production. However, the collection of water charges was started on 1976-77 at a nominal rate of 3% of the increased benefit. In early eighties the donor agencies prescribed the Government of Bangladesh (GoB) to realize a significant part of the O&M cost of irrigation from the project beneficiaries. Supporting the donor agencies recommendations, GoB promulgated the new 'Irrigation Water Rate Ordinance' in 1983 together with the new 'Water Rate Rules' in 1984. Few years later the donor agencies observed that practiced water rates was not enough to realize the O&M cost of the projects and they suggested to revise the irrigation water rates. Following such prescriptions, GoB issued 'The Amendment of the Irrigation Water Rate Ordinance' in 1990 with the modified rules of Irrigation Water Rates in 1992 (Sattar, 1999).

Since rice is the prevalent crop for all projects, its benefit was considered as the yardstick of estimating the water rates in different seasons. The water rate was set by considering the yield and water consumption by the crop. According to the latest regulation on 1992, water users committees would be formed and the committee is responsible for irrigation management at farm level and for collection of the water charges.

In the Teesta Irrigation Project (TIP) the price of irrigation water was imposed recently in 2004 based on the land area irrigated rather than the quantity of water used by different crops or farmers. The water rate at TIP is fixed by BWDB as US$ 16.90 (Tk[1] 1,200) per hectare per year whereas individual farmers need to pay US$ 24.37 (Tk 1,730) to the Water Users Association (WUA). However, BWDB is still working to form the WUA for the entire TIP and to bring all the farmers under the payment system (BWDB, 2008).

[1] Tk indicates Taka, the national currency of Bangladesh worth 71:1 US$ in January 2011

5.2 Data and methods

Considering the present context and data availability, residual imputation method (RIM) based on the actual market prices of the inputs and outputs is chosen and applied in estimating the economic value of water used for agricultural purpose at TIP. For this study, information on the quantity of water used in the project area or water applied to the specific crop was not available. The production cost information was available as aggregated over the crop growing period and for the whole project area rather than the individual farm level. In such a situation, irrigation water requirements over the existing whole project irrigated area are considered as a proxy of the actual irrigation water use at farm level. Input costs and output benefits are estimated using residual imputation approach to impute economic value to the water used at project level. A production model estimating the crop yield due to the assumed hypothetical water shortage with different quantities is considered as the basis to estimate the marginal benefit function of water used in agriculture.

Irrigation water requirements for the crops and the aggregated demand at the project level are estimated using CROPWAT model for all the crops except rice. A water balance model (Mohan et al., 1996) is used to estimate the irrigation water requirement for the lowland rice. Information on the input quantities required for and the output (yield) from the production process of the individual crops are available at the project level from the TIP evaluation study by BWDB (2005). Residual imputation method (RIM) is then applied for estimating the irrigation water value. Scenarios with different level of water-shortage are assumed and RIM is applied for all scenarios, which depicts the value of irrigation water at different water availability levels. This relationship in fact forms the total benefit function for the irrigation water use at TIP. The first order derivative of this total benefit function gives the marginal benefit function.

5.2.1 Estimation of water requirement

5.2.1.1 Land use and cropping pattern at TIP

Information of the current land use and cropping patterns are collected from BWDB. Three different types of rice (*Aus*, *Aman*, *and Boro*) and other main crops like maize, tobacco, potato, oil seeds, pulse and vegetable are grown in the project area. Based on the season, the crops grown and area cultivated and irrigated under each crop are presented in Table 5.2. Figure 5.1 shows the crop calendar for irrigated crops at the Teesta Irrigation Project. Only the dry season crops (cabbage, cauliflower, potato, tobacco, tomato and wheat) along with the three different varieties of rice need irrigation.

Table 5.2 Agricultural land use patterns at TIP

Cropping Pattern			**Net irrigated area (ha)**	**Irrigated cropped area (ha)**	**% of Net Area**
***Kharif* -I**	***Kharif* -II**	***Rabi***			
Aus HYV	*Aman* HYV	Fallow	941	1,882	0.84
Fallow	*Aman* HYV	Wheat	13,167	26,334	11.78
Aus HYV	*Aman* HYV	Fallow	5,342	10,684	4.78
S. Vegetables	*Aman* HYV	Fallow	2,188	4,376	1.96

Cropping Pattern			**Net irrigated area (ha)**	**Irrigated cropped area (ha)**	**% of Net Area**
***Kharif* -I**	***Kharif* -II**	***Rabi***			
Others	*Aman* HYV	Fallow	977	1,954	0.87
Fallow	*Aman* HYV	Kaon	1,222	2,444	1.09
Aus HYV	Others	Fallow	1,745	3,490	1.56
Fallow	*Aman* LV	Others	576	1,152	0.52
Fallow	*Aman* LV	*Boro* HYV	7,347	14,694	6.58
Others	*Aman* LV	Fallow	3,350	6,700	3.00
Fallow	*Aman* HYV	*Boro* HYV	53,490	106,980	47.87
Fallow	*Aman* HYV	Maize	370	740	0.33
Fallow	*Aman* HYV	Tobacco	552	1,104	0.49
Fallow	*Aman* HYV	Oil Seeds	353	706	0.32
Sub-total of Double Crops			***91,620***	***183,240***	***82.00***
Aus HYV	*Aman* HYV	Pulses	483	1,449	0.43
Aus HYV	*Aman* HYV	Oil Seeds	250	750	0.22
Jute	*Aman* HYV	Tobacco	9,219	27,657	8.25
S. Vegetables	*Aman* HYV	Potato	7,665	22,995	6.86
Others	*Aman* HYV	W. Veg	2,495	7,485	2.23
Sub-total of Triple Crops			***20,112***	***60,336***	***18.00***
Total Cropped Area				***243,576***	
Net Area			***111,732***		
Cropping Intensity (%)				***218***	

Note: LV = local variety; HYV = high yield variety
Source: BWDB, 2005

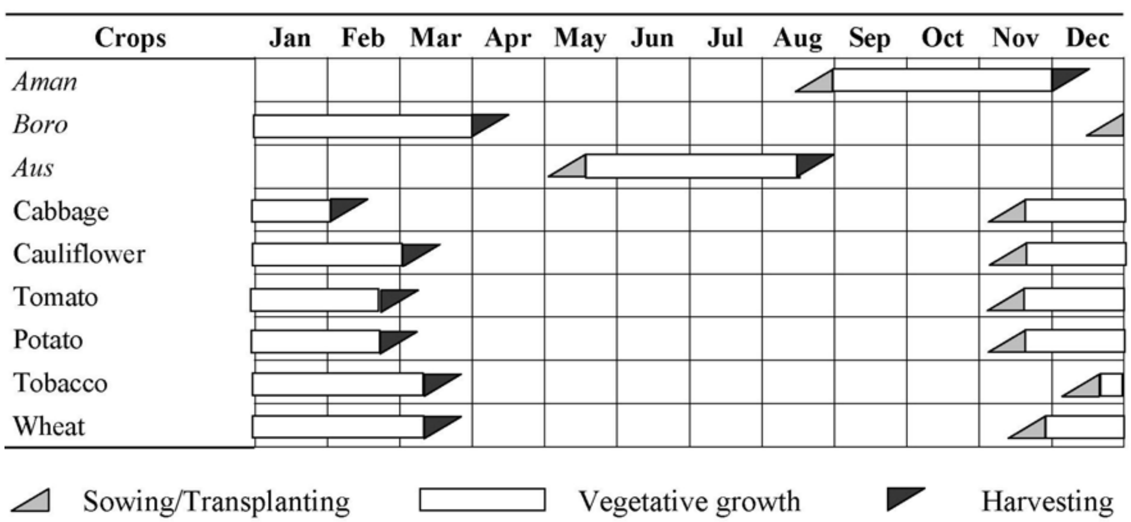

Figure 5.1 Crop calendar for Teesta Irrigation Project
Source: BWDB, 2005

5.2.1.2 *Potential evapotranspiration (ET_0)*

Potential evapotranspiration is calculated using the Penman-Montieth method. The mean monthly temperature, relative humidity and wind speed of Dinajpur district (the district inside TIP) is used from FAO database. The potential evapotranspiration is calculated using CROPWAT (version 4.3 for WINDOWS) model and shown in Table 5.3.

Table 5.3 Climatic data and ET_0 at TIP

Month	Max Temp (^oC)	Min Temp (^oC)	Humidity (%)	Wind speed (km/d)	Sunshine (hr)	Solar radiation ($MJ/m^2/d$)	ET_0 (mm/d)
January	24.9	10.3	75	26	8.7	15.8	***2.06***
February	27.3	12.3	67	43	9.0	18.3	***2.88***
March	32.3	16.7	56	60	9.7	21.8	***4.20***
April	35.4	21.2	59	86	9.6	23.6	***5.36***
May	33.8	23.7	74	104	8.4	22.6	***5.19***
June	32.2	25.3	82	95	5.4	18.2	***4.19***
July	31.6	26.2	85	86	4.7	17.0	***3.88***
August	31.6	26.0	85	69	4.4	16.1	***3.63***
September	31.4	25.5	85	60	5.2	16.0	***3.49***
October	31.2	22.3	81	35	7.9	17.6	***3.39***
November	28.8	16.1	76	26	8.9	16.4	***2.52***
December	25.9	11.7	76	35	9.0	15.3	***2.05***

Source: IWM, 2003

5.2.1.3 *Soil characteristics and Seepage & percolation (S&P) rate*

Teesta Irrigation Project falls within the Agro-Ecological Zone – 3 (AEZ-3) 'Teesta Meander Flood Plain', with a small part in AEZ-25 'Barind Tract' and AEZ-27 'North Eastern Barind Tract'; where the whole country is divided into 30 Agro-Ecological Zones. Soil type in Teesta Meander Flood Plain (AEZ-3) is in general Eutric Gleysols type which is a non-calcareous grey soil (Banglapedia, 2009). This type of soil consists of 6% sand, 6% clay and 88% loam (FAO, 2004). Institute of Water Modeling (IWM, 2003) conducted a study on TIP soil characteristics. Soil samples from 12 locations were collected and tested. The soil texture was found varies between silt, silt loam, sandy silt, sandy loam to loamy sand.

Seepage (S), the lateral subsurface flow of water from a bunded rice field and percolation (P), the downward flow of water below the root zone occur simultaneously during land preparation and crop growth period and are governed by the water head (depth of pounded water) on the field and the resistance to water movement in the soil. Due to the difficulty in separation between seepage and percolation in the field, S and P are often taken together as one term, S&P. The S&P value for TIP region is assumed as 3 mm/d based on literature (e.g. IWM, 2003).

5.2.1.4 Mean aerial Rainfall at Teesta Irrigation project area

Observed rainfall data from six stations in and around TIP for the last ten years (1998 to 2007) are collected from BWDB central database. Station weighting factors are calculated from Thiessen Polygon method. The monthly mean aerial rainfall (mm) for all these stations and the mean rainfall for TIP area are shown in Table 5.4.

Table 5.4 Average rainfalls (mm) at TIP area (1998 - 2007)

Station	ID	Wt	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Badargonj	CL153	0.16	6.3	10.1	31.1	112.4	173.8	385.3	449.8	330.1	323.9	340.6	8.1	6.9
Bagdorga	CL154	0.20	1.3	5.3	9.5	105.4	207.9	420.0	481.6	279.1	291.8	292.5	1.8	0.0
Dimla	CL167	0.27	9.5	4.3	30.2	135.7	255.4	620.6	538.0	492.6	431.7	301.0	6.6	2.1
Kaligonj	CL177	0.08	12.3	13.6	48.0	152.7	253.8	489.4	510.5	380.2	328.8	207.8	12.2	13.0
Mahipur	CL188	0.05	1.3	16.8	31.5	83.7	335.7	442.6	735.4	248.2	277.9	292.6	2.1	5.4
Saidpur	CL210	0.24	8.3	11.4	16.0	166.9	306.3	581.7	592.0	342.9	328.7	190.7	4.0	2.1
Weighted Mean			***6.9***	***8.5***	***24.3***	***132.1***	***248.9***	***514.1***	***533.2***	***366.7***	***345.8***	***271.3***	***5.5***	***3.5***

Source: BWDB database, 2008

5.2.1.5 Irrigation requirement

In addition to the dominant rice crop, several crops are grown in TIP area. However, only the dry season crops along with the three rice varieties need irrigation water and are considered for the irrigation water estimation in this study. The dry season crops in the TIP area are cabbage, cauliflower, potato, tobacco, tomato and wheat. Irrigation water requirements for the crops except the rice are estimated using CROPWAT model for WINDOWS version 4.3 (FAO, 1998). A water balance approach is employed to estimate the irrigation water requirement for rice crop (as shown in Figure 5.2). All the rice varieties in the project area are of the lowland type, therefore the water balance approach encompassing the field water balance components (Equation 5-1), proposed by Mohan et al. (1996) fits well and used here in estimating irrigation water requirements for the rice.

$$S_t = S_{t-1} + I_t - ET_{ct} + ER_t - SP_t \tag{5-1}$$

Where, S_t indicates storage in the bund at the end of time period t; S_{t-1} is the storage at the beginning of time period t; I_t refers applied irrigation during the period t; ET_{ct} is actual evapo-transpiration by the rice crop during the period t; ER_t refers to effective rainfall during the period t and SP_t indicates seepage and percolation losses during time period t. One day is considered as the unit time period in water balance simulation calculation. All the components of field water balance are in mm.

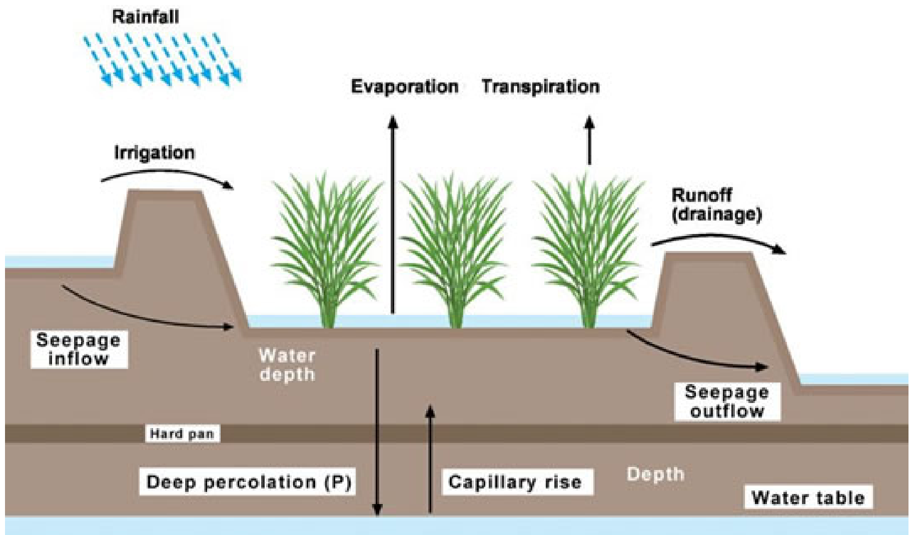

Figure 5.2 Typical water balance for low land rice field

The concept of standing water is explicitly incorporated in this water balance. The method assumes that the paddy field can store additional rainfall up to the level of field-bund (spillway). Seepage and percolation loss (3 mm/d) is assumed to occur for the first 105 days when the ponding condition exists and afterwards the rice field is considered in a drained condition for last 15 days where the total growth period of the rice crops are 120 days. Featuring the typical local practices, ponding depth in rice field is assumed to be at least 50 mm with a maximum up to 100 mm. In case of excess rainfall beyond the field-bund capacity, the excess rainwater goes out from the system as runoff. In addition, water requirement for nursery (nursery is assumed in 5% of respective rice area cultivated) and land preparation are accounted for. Crop coefficient of rice for different stages of crop growth and corresponding length in days are used as mentioned in Table 5.5.

Table 5.5 Crop coefficient and duration of different stages of rice

Stage	**Crop coefficient**	**Length (day)**	**Total length (day)**
Land preparation	….	20	20
Nursery	1.20	30	30
Initial stage	1.10	20	120
Development stage	1.10	30	
Mid season	1.25	40	
Late season	1.00	30	

Source: IWM, 2003

5.2.1.6 Water requirement for land preparation

Water used for land preparation varies widely; however, literature suggests this requirement as about 150 – 250 mm for the tropical and sub-tropical Asian countries (Bhuiyan 1992; Guerra et al., 1998). Ghani et al. (1989) reported the water requirement for land preparation in G-K (Ganges-Kabotak) Irrigation project, Bangladesh is as high as 1,500 mm. Ghani et al. (1989) did the study both in farmer-managed (tertiary) field and researcher-managed field and the results are presented in Table 5.6. However, water requirement for land preparation for this study is assumed 180 mm for a period of 20 days.

Table 5.6 Water required for land preparation (mm) in Ganges-Kabotak Irrigation Project in Bangladesh

Year	***Aus***		***Aman***	
	Farmer-managed plot	**Researcher-managed plot**	**Farmer-managed plot**	**Researcher-managed plot**
1983	110 – 970 (465)	---	150 – 1,075 (510)	---
1984	190 – 1,865 (733)	175 – 275 (235)	200 – 695 (485)	95 – 315 (260)
1985	205 – 5,120 (1,460)	230 – 255 (248)	175 – 115 (440)	170 – 260 (215)

Note: Figure in parenthesis is the average
Source: Ghani et al. (1989)

Two measures of water are of interest, namely: water use requirement at field (WRF) and water withdrawal requirement from the source (WWR). Water use requirement at field refers to the amount of water actually required at the field level, which includes evapotranspiration, seepage and percolation, land preparation as well as maintaining ponding condition in case of rice. Requirements for leaching of salts and pre-irrigation are not considered. Water withdrawal from the source refers to the amount of water required to be diverted at the barrage which is met by available surface water otherwise farmers abstract groundwater. Water withdrawal requirement would be always higher than WRF due to losses in conveyance. The ratio of WRF to WWR is defined as the overall efficiency of the irrigation project.

Although rapid expansion of the irrigated area has been reported over the country in the recent past, water use efficiency is still poor (Dey et al., 2006). On the other hand data on overall irrigation efficiency is scarce and no specific information on irrigation efficiency for TIP is found in the literature. Dey et al., (2006) reported the average distribution loss is 45% all over the country. IWM (2003) used application efficiency as 70% while developing decision support services for the irrigation systems and management for the TIP. For this study, overall efficiency (including conveyance, field channel and field application) of the TIP irrigation system is assumed to be 40%.

5.2.2 Estimation of water value – Residual Imputation Method (RIM)

The residual imputation method accounts the incremental contribution of each input in a production process. Using the market mechanism, if the correct prices – equal to their marginal returns – are assigned to all input resources used in a production process except one (water in this particular case), the remainder of total value of the product is imputed to the remaining or the residual input resource (Young, 1996; Agudelo, 2001). Residual valuation thus assumes that total value of production can be divided into shares, in such a way that each resource is paid according to its marginal productivity and total product is completely exhausted (Young, 1996). Following this principle the total value product (TVP) equals the opportunity cost of all the inputs (Agudelo, 2001) as expressed in Equation 5-2.

$$TVP = \sum VMP_i * Q_i + VMP_w * Q_w \tag{5-2}$$

Where, *TVP* implies total value of the commodity produced; VMP_i indicates the value of marginal product of input *i*; Q_i is the quantity of input *i* used in production, *w* stands for water.

Following Equation 5-2, shadow price of water can be obtained; it indicates the maximum amount the farmer could pay for water and still can cover the cost of production when the marginal value product of all inputs are considered as their market price. Therefore, Equation 5-2 can be rearranged to estimate the *VMP* of water (Equation 5-3):

$$VMP_w = \frac{TVP - \sum P_i * Q_i}{Q_w} \tag{5-3}$$

Where, P_i is the price of input *i*. Information on the quantities of inputs for and output from the crop production process are taken from TIP evaluation report (BWDB, 2005). Market prices as of June 2008 for the agricultural inputs and outputs are considered in the residual imputation analyses.

5.2.3 Estimation of total and marginal benefit function of irrigation water

Values of water at different assumed water availability levels incorporating with the water availabilities form the basis in estimating the total and marginal benefit functions for irrigation water (based on Equation 3-1). Three different scenarios are also employed (i) conjunctive use of groundwater to meet the shortage in available river water, (ii) reduction in irrigated land area to execute full irrigation with reduced supply from river and (iii) yield response to water stress when insufficient water supply covers fully the existing irrigated crop area. Five different levels of water shortage (10%, 20%, 30%, 40% and 50%) from the maximum water withdrawal requirement are considered. Residual imputation method gives the irrigation water value for each level of water shortage for all three scenarios.

Groundwater abstraction volume and irrigated land area reduction are proportionate to water shortage at diversion point in the river. However, efficiency in using groundwater can be considered higher than river water because of its small scale management, less conveyance and immediate and high payment requirement. An efficiency of 70% is used in case of groundwater irrigation. Concerning the cost of groundwater abstraction, farmers within TIP area as well as at the left bank of Teesta where the farmers depend fully on groundwater were asked at the time of field visit. It was revealed that the groundwater abstraction cost is about US$ 0.0085 (Tk0.60) per m^3. Normally farmers rent the pump to irrigate their field, hence the cost indicates the cost of pump (annualized capital cost) and pumping (operation) in together. Chowdhury (2005) mentioned the groundwater irrigation cost is about US$0.0076 (Tk0.54) per m^3 in Northwest region of Bangladesh; however, taking into consideration of oil price hike in the recent past, farmers' estimation is considered for the study.

The ratio of actual to maximum evapotranspiration quantifies the yield response to water stress. Equation 5-4 shows the relationship which was proposed by Doorenbos and Kassam (1979).

$$Y_a = Y_{max}\left[1 - k_y\left(1 - \frac{ET_a}{ET_{max}}\right)\right] \tag{5-4}$$

Where, Y_a is the actual harvested yield (t/ha), Y_{max} is the potential yield (t/ha), k_y is the average yield response factor (non-dimensional) for the overall growth period and ET_a and ET_{max} refers to actual and maximum evapotranspiration (mm) respectively. Value of E_{max} is taken from CROPWAT model calculation. However, Equation 5-4 can be applied for crops other than rice because water requirement for lowland rice does not refer only the evapotranspiration. An empirical study on Indian lowland rice by Bouman and Tuong (2001) provides the production function (Equation 5-5) in terms of water input.

$$Y_a = Y_{max}\left(1 - e^{-b(waterinput - 300)}\right) \tag{5-5}$$

Where, Y_a and Y_{max} are the actual and potential yield (t/ha) respectively, b is the initial factor (water in this case) use efficiency or the initial slope (dimensionless value in the range of 0.00175 – 0.00275), *waterinput* is the water application that includes applied irrigation water including effective rainfall (mm). The figure 300 in Equation 5-5 indicates the minimum amount of water input for any yield at all. Potential yield values (Y_{max}) are taken from the TIP evaluation report (BWDB, 2005).

Microeconomics considers the firm's production process through the relationship between the input requirement and the production output. For many purposes it is useful to represent the relationship between inputs and outputs using a mathematical function often termed as the production function that maps vectors of inputs into a single measure of output. A production function is often approximated using polynomials. For the case of a single input, such as river discharge, with a single output per firm (i.e. crop production), a quadratic production function (synonymously used as total benefit function hereafter) would reflect appropriately the usual shape of the relationship: while input use increases, output first increases then stabilizes, then decreases. In this study a quadratic relation (Equation 3-1) between net benefits and river flow is considered to obtain the total benefit (TB) function for river water diverted to irrigation use where flow indicates the river discharge. The first order derivative of the total benefit function (Equation 3-1) with respect to *flow* (Q) gives the marginal benefit function.

5.3 Results

5.3.1 Irrigation water requirements and water availability

Tables 5.7 and 5.8 present the net irrigation water requirements at field along with the effective rainfall for rice and other crops respectively. In case of rice, the effective rainfall is estimated from the field water balance study (Equation 5-1) pertaining to maintain the ponding condition in the field after transplantation of the rice plants. Dry season rice, *Boro* needs the highest irrigation requirement of 1,019 mm at field level. Effective rainfall for other crops is estimated using the USDA soil conservation service method embedded in the CROPWAT modeling. Other than rice, cauliflower needs the highest amount of water for irrigation, i.e. 346 mm, whereas cabbage needs 228 mm.

Table 5.7 Irrigation water requirements at field (WRF) for different types of rice crops grown in Teesta Irrigation Project area

Rice (growing period)		Water requirement and rainfall at field			
		Total WRF (mm)	**Effective rainfall (mm)**	**Net WRF (mm)**	**Total (mm)**
Aman (D2 Jul – D2 Dec)	Nursery	136	353	0	
	LP	180	215	0	
	Growing stage	783	633	150	150
Aus (D1 Apr – D3 Aug)	Nursery	193	105	88	
	LP	180	70	110	
	Growing stage	979	924	52	250
Boro (D2 Nov – D2 Apr)	Nursery	83	4	79	
	LP	180	2	178	
	Growing stage	834	72	762	1,019

Note: LP = Land preparation; CWR= Crop water requirement including the water requirements to maintain ponding condition; D1, D2 and D3 are 1-10, 11-20 and 21-30 dates of each month

Table 5.8 Irrigation water requirements at field (WRF) for the dry season crops grown in Teesta Irrigation Project area

Crop (growing period)	Water requirement and rainfall at field		
	Total WRF (mm)	**Effective rainfall (mm)**	**Net WRF (mm)**
Cabbage (D1 Nov – D2 Feb)	228	0	228
Cauliflower (D1 Nov – D2 Mar)	367	21	346
Potato (D1 Nov – D1 Mar)	334	10	324
Tobacco (D1 Dec – D3 Mar)	310	22	288
Tomato (D1 Nov – D1 Mar)	340	10	330
Wheat (D2 Nov – D3 Mar)	297	22	275

Note: D1, D2 and D3 are 1-10, 11-20 and 21-30 dates of each month

Table 5.9 presents the WRF and WWR on monthly basis for the irrigation season. Water withdrawal requirement is further converted into flow (m^3/s) with an appropriate conversion from its depth unit (mm) based on the water requirement for each crop in specific month with the consideration of area irrigated under the individual crops. Details on crop wise monthly irrigation requirements are given in Tables B.1 and B.2 of Appendix B. Month of December needs the highest irrigation supply, which is about 466 mm at the project level, corresponds to 194.4 m^3/s of flow diversion. November, February, January and March follow subsequently according to the demand for irrigation water withdrawal. *Boro* rice shares the largest part of this irrigation demand. Monthly share of the irrigation demand is also presented in Table 5.9. Daily mean discharge for the last three years at the TIP barrage provides the water availability, which is compared with the WWR. Even though TIP authority did not reveal the actual water diversion information, the personal communication with the field engineer at the barrage site provides an idea on water diversion practices especially for the water shortage period. In general 90% of the available water at the barrage is diverted to the irrigation canal if the WWR goes higher than the availability otherwise diversion follows the actual WWR. Based on this statement, the last two columns in Table 5.9 represent the monthly WWR that is fulfilled from the river water diversion.

Table 5.9 Irrigation water requirement at field (WRF), water withdrawal requirement (WWR), available flow at the barrage and diversion to the Teesta Irrigation Project

Month	WRF (mm)	WWR (mm)	WWR[a] (m^3/s)	Share for *Boro* rice (%)	Water availability[b] (m^3/s)	Diversion[c] (m^3/s)	Diversion (mm)
November	154	384	165.7	20	237.1	165.7	384
December	186	466	194.4	78	149.2	134.3	322
January	128	320	133.6	80	65.4	58.8	141
February	139	348	160.9	78	65.6	59.0	128
March	123	308	128.3	89	77.1	69.4	166
April	26	64	28.6	66	236.8	28.6	66
Total	756	1,890	---		---	---	1,207

Note: [a]Unit conversion of WWR from mm to m^3/s is based on water requirement for each crop in specific month with the consideration of irrigated area under each crop
[b]Water availability is based on last five years (2002 - 2006) flow at the TIP barrage
[c]When WWR>Water availability, diversion = 0.9*Water availability;

5.3.2 Value of irrigation water

Table 5.10 presents the irrigation water value for each crop based on the RIM calculation. The details of the RIM calculation with each input and output price is reported in Tables B.3 and B.4 of Appendix B. Water value estimation presented in Table 5.10 considers no water-stress to the crops implying highest possible yield and the case of entire irrigation supply from the river water diversion.

Table 5.10 Value of irrigation water for different crops grown in the Teesta Irrigation Project area at no water-shortage condition

Crops	Area irrigated (ha)	Input cost (US$/ha)	Harvest value (US$/ha)	WWR (m^3/ha)	Value of water (US$/$10^3$ m^3)
Aman LV	11,273	406	562	3,750	41
Aman HYV	98,714	481	733	3,750	67
Aus	7,820	467	567	6,250	16
Boro	60,837	656	852	25,475	8
W.Veg	2,495	593	901	7,533	41
Potato	7,665	901	1,056	8,093	19
Tobacco	9,771	733	1,056	7,195	45
Wheat	13,167	385	775	6,875	57
Weighted average	111,732	1,041	1,484	18,900	24

Note: LV = Local variety; HYV = High yield variety; W.Veg = Winter Vegetables: cabbage, cauliflower and tomato in together; WWR = Water withdrawal requirement at source (TIP barrage)

Among all the crops grown in the TIP using irrigation water, *Aman* HYV rice generates the highest irrigation-water value of US$ 67 per 10^3 m^3 (Tk4.75 per m^3). *Boro* rice shares the largest part of irrigation water and results the lowest irrigation water value of US$ 8 per 10^3 m^3 (Tk0.55 per m^3). Chowdhury (2005) calculated the irrigation water value US$ 8 per 10^3 m^3 (Tk0.54 per m^3) for *Boro* rice in the Northwest region of Bangladesh.

Table 5.11 represents the summary results of RIM analysis for the whole TIP project. Average net income from the crop production using irrigation water of 1,890 mm is US$ 444 (Tk 31,510) per ha which shows an average value of diverted irrigation water US$ 24 per 10^3 m^3 (Tk1.67 per m^3). However, Table 5.9 recalls that the present status of flow at the barrage does not support the diversion of the entire WWR. For the irrigation season six months total 1,207 mm of water is available for diversion out of the total requirement of 1,890 mm. The deficit in irrigation water supply from the river is met by groundwater abstraction which amounts [(1,890-1,207)*0.4/0.7=] 390 mm to be applied evenly over the full irrigated area and season. In a study, Wahid et al. (2007) showed the groundwater abstraction in TIP is in the range of 296 to 860 mm. Accounting the cost of groundwater irrigation [3,900(m^3/ha)*0.0085(US$/$m^3$) = 32.95 US$/ha equivalent to 2,340 Tk/ha] as an individual input in RIM yields the diverted river water value of [(444–32.95)/12,070=] US$ 0.034 (=Tk 2.42) per m^3.

Table 5.11 Irrigation water value at the project level of Teesta Irrigation Project with no water-shortage condition

Parameter	**Value**
Net irrigated area (ha)	111,732
Average input cost[a] (US$/ha)	1,041 (Tk73,879/ha)
Average harvest value[a] (US$/ha)	1,484 (Tk105,390/ha)
Net income from entire project (10^6 US$)	49.59 (Tk 3,520 mil)
Total water use at field (m^3/ha)	7,560
Total WWR (m^3/ha)	18,906
Average monthly discharge requirement at barrage (m^3/s)	136
Avg. value of irrigation water used (US$/$10^3$ m^3)	59 (Tk 4.17/m^3)
Avg. value of irrigation water diverted (US$/$10^3$ m^3)	24 (Tk 1.67/m^3)
Marginal value of diverted discharge at full supply (10^6 US$ per m^3/s)	0.06 (Tk 4.17x10^6)

Note: [a]average input cost and harvest value are calculated by adding up the cost/values for individual crops and then averaged over net irrigated area

5.3.3 Total and marginal benefit function

Following RIM, the overall benefit from agricultural production using irrigation water at the TIP is calculated for five different water shortage levels in three different scenarios. Total benefits are distributed over the year uniformly and presented on monthly basis. Deducting the hypothetical water shortages from the entire WWR represents the water availability levels in the river. Water availability is further reported as the mean flow over six months of the irrigation period.

Table 5.12 represents the water availability and monthly benefit at different water shortage levels and scenarios. The water availability and monthly benefits are used to develop the quadratic total benefit function (Equation 3-1) for the irrigation water for the three different scenarios as presented in Equation 5-6 (a) – (c). The TB values obtained from Equation 5-6 are in million US$ per month.

Table 5.12 Monthly benefits (10^6 US$) to be imputed to irrigation water at different water shortage levels in three different scenarios

	Water shortage in % of Water withdrawal requirement from river					
	0%	*10%*	*20%*	*30%*	*40%*	*50%*
Water availability, m^3/s (mm)	135.8 (1,890)	122.2 (1,701)	108.6 (1,512)	95.0 (1,323)	81.5 (1,134)	67.9 (945)
S1	8.26	8.09	7.92	7.75	7.58	7.41
S2	8.26	7.44	6.61	5.79	4.96	4.13
S3	8.26	7.42	6.51	5.54	4.48	3.33

Note: *present water availability level in the river; S1 = scenario 1 – groundwater abstraction meets the shortage in river water availability; S2 = Scenario 2 – execution of full irrigation to reduced land in case of insufficient flow in river; S3 = Scenario 3 – yield loss due to water stress in case of insufficient flow in river

For S1, $TB_{irr} = 0.013 * flow + 6.565$ (5-6a)

For S2, $TB_{irr} = 0.061 * flow - 0.0005$ (5-6b)

For S3, $TB_{irr} = -0.0002 * flow^2 + 0.115 * flow - 3.493$ (5-6c)

Table 5.13 presents the coefficient values of the total benefit function as well as the last column reports the marginal benefit functions. In the first two scenarios, conjunctive use of groundwater and reduced irrigated land, the coefficients of $flow^2$ and *flow* appear zero and positive non-zero value respectively indicating a straight line with positive slope for the TB functions and with zero slopes MB functions. However, for the third scenario, yield response to water stress, the coefficient of $flow^2$ is negative and for *flow* it has positive value that indicates a quadratic TB function and a MB function having downward slope with a positive MB value initially. Figures 5.3 and 5.4 represent the total benefit and marginal benefit functions for three different scenarios respectively. Results show that in case of less water available for diversion at the barrage, filling the demand by groundwater is the most profitable and that is currently under practice.

Table 5.13 Regression analysis results based on Equation 3-1 and marginal benefit functions of river water in irrigation use

Scenario	Parameter values of TB function			Marginal benefit function
	β0	*β1*	*β2*	
S1	6.5649	0.0125	0	*MB = 0.0125*
S2	0.0005	0.0609	0	*MB = 0.0609*
S3	-3.4925	0.1145	-0.0002	*MB = -0.0004*flow + 0.1145*

Note: S1 = scenario 1 – groundwater abstraction meets the shortage in river water availability; S2 = Scenario 2 – execution of full irrigation to reduced land in case of insufficient flow in the river; S3 = Scenario 3 – yield loss due to water stress in case of insufficient flow in the river

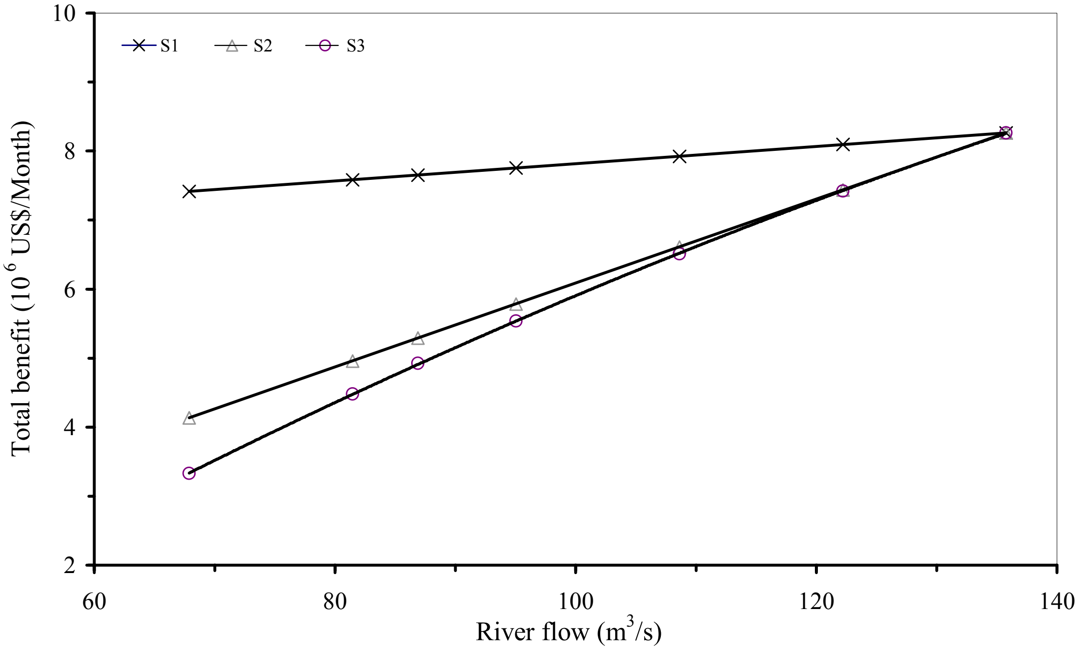

Figure 5.3 Total benefit functions for the irrigation water use at Teesta irrigation project

Note: S1 = scenario 1 – groundwater abstraction meets the shortage in river water availability; S2 = Scenario 2 – execution of full irrigation to reduced land in case of insufficient flow in river; S3 = Scenario 3 – yield loss due to water stress in case of insufficient flow in river

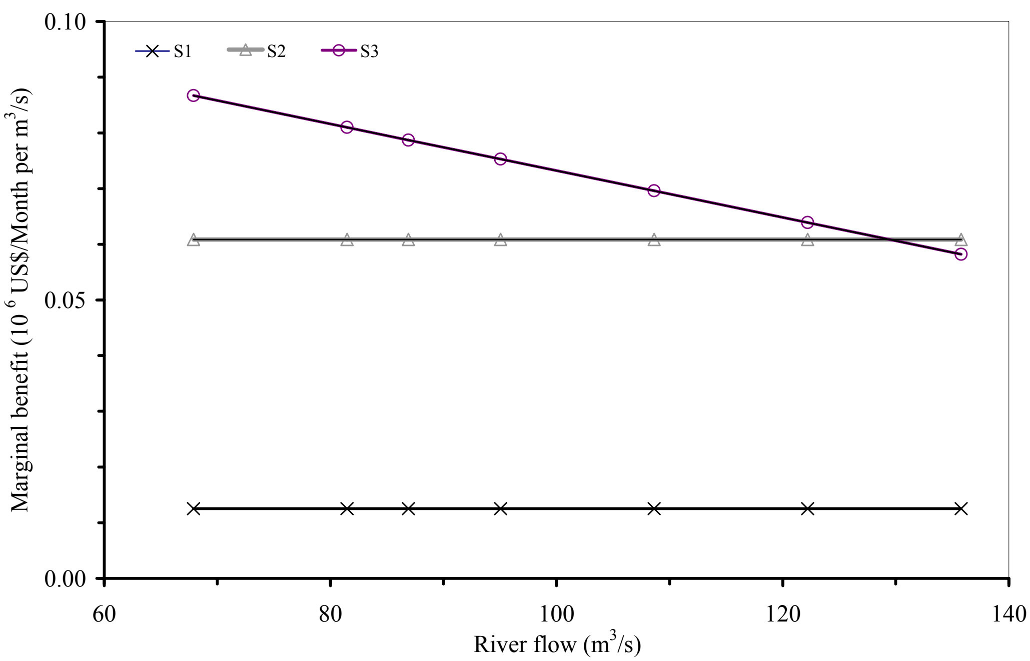

Figure 5.4 Marginal benefit functions for the irrigation water use at Teesta irrigation project

Note: S1 = scenario 1 – groundwater abstraction meets the shortage in river water availability; S2 = Scenario 2 – execution of full irrigation to reduced land in case of insufficient flow in river; S3 = Scenario 3 – yield loss due to water stress in case of insufficient flow in river

Analyses based on residual imputation method indicate that the average value of withdrawn irrigation water for TIP, US$ 24 per 10^3 m^3 (Tk 1.67 per m^3) is much higher than the current irrigation fee of US$ 1.3 per 10^3 m^3 (Tk 0.09 per m^3) considering US$ 24.36 (Tk 1,730) is paid for 18,900 m^3 of withdrawn irrigation water per hectare of land. An average monthly flow of 136 m^3/s can meet fully the irrigation demand of TIP and can generate the maximum total benefit of about US$ 50 million (Tk 3,520 million) for the whole irrigation season over the entire project. Since the irrigation season is only for six months, the benefit is distributed uniformly over the irrigation season and that results the total benefit of US$ 8.33 million (Tk 587 million) per month. At the full supply level (full demand met from river water) the marginal benefit is about US$ 0.059 million (Tk 4.16 million) per m^3/s as monthly basis. In the same scenario, the marginal benefit would increase to US$ 0.087 million (Tk 6.15 million) per m^3/s per month when the flow decreased to half (68 m^3/s).

5.4 Discussions and concluding remarks

The study develops the total and marginal benefit functions with respect to withdrawn flow, such approach is rarely reported in literature. Since most in-stream uses relate with flow rather than volume of water, using flow as the basis to develop the economic benefit functions enable to compare the benefit of off-stream uses with in-stream uses in the optimization model. Part of the withdrawn flow is not actually used in irrigation system and it goes either to surface drainage system or percolates down into the ground and meets to groundwater aquifer; these issues, however, have not been considered in estimating the value of water in this study. The study reveals that the value of withdrawn water for meeting the irrigation demand is US$ 0.024 (Tk 1.67) per m^3 and US$ 0.058 million (Tk 4.16 million) per m^3/s per month at the full supply level.

Average values of diverted and applied irrigation water for TIP are respectively estimated as about US$ 0.024 (Tk1.67) and US$ 0.06 (Tk 4.17) per m^3. Hussain et al. (2007) reported the values of irrigation water having different denominators for several irrigation systems in different countries; e.g. they mentioned the value per m^3 of supplied irrigation water for Mahi Kadana system, India as US$ 0.04-0.07 (for all crops in year 1995-1996); per m^3 of diverted water for Kirindi Oya basin, Sri Lanka as US$ 0.027 (for rice in year 1999); per m^3 of supplied water in Chistian Sub-division, Pakistan as US$ 0.04 (for all crops in 1993-1994); per m^3 of diverted water for Nam Thach Han system, Vietnam as US$ 0.045 (for all crops in 2001-2003).

Two principal axioms are embedded with RIM analysis: the prices of all resources are equated to returns at the margin (competitive equilibrium market) and the total value of the product is divided into shares. However, for the developing countries in general, the agricultural sector is subsidized through some of its inputs mainly the fertilizer, pesticide and irrigation water. This issue has not been considered in estimating the value of irrigation water in this study. This may have resulted in overestimation of the value of irrigation water. Water quality aspect of water withdrawn for irrigation is not considered.

The assumed water shortages applied at the field level is synonymous to deficit irrigation; however, economics and management of deficit irrigation are not addressed and that might have resulted in underestimation of the value of water in this study. Present study only estimates the value of irrigation water based on the existing situation keeping the present circumstances unvarying including the inputs to the crop production system.

6 BENEFIT FUNCTIONS OF INSTREAM WATER USES IN THE TEESTA RIVER

The instream water direct uses for the Teesta are capture fishery and navigation as already mentioned in Chapter 4. This chapter illustrates the estimation of the total and marginal benefit functions for the instream water uses.

6.1 Introduction

Despite considerable progress on understanding and recognition of in-stream water requirements, successful cases of environmental flow implementations are quite few. Developing countries are particular cases in point. Reallocation of water among sectors is often demanded and prescribed; however, such actions can be myopic, unless potential repercussion towards the socioeconomic benefits and costs are well documented and addressed. Moreover, a number of researches (e.g. Moore, 2004; Scatena, 2004) argue that better understanding of socio-economic benefits and costs involved with instream water provisioning is essentially required to justify sustaining in-stream flow.

Relatively accurate information on marginal value of offstream uses is available; however, measuring economic value of in-stream uses for alternative flow levels is a different problem. To date, there have been a number of researches that have tried to value in-stream water uses, mainly recreational boating, fishing, rafting, and the like. Majority of these researches applied contingent valuation method (CVM) and travel cost method (TCM) predominantly in developed countries. Examples include: use of CVM in Cache la Poudre River in Northern Colorado, USA (Daubert and Young 1981); Montana's Big Hole and Bitterroot Rivers, USA (Duffield et al. 1992); Colorado River (Booker and Colby 1995); in Idaho and California (Loomis 1998); application of CVM and the Travel Cost Method (TCM) in California, USA (Douglas & Taylor 1998); use of TCM in California, USA (Weber & Berrens 2006). Some studies valued in-stream water for endangered and at-risk fish species for example, Berrens et al. (1996); Loomis (1998); Hickey and Diaz (1999); and some studies estimated the bequest and existence values e.g. Loomis (1987); Brown and Duffield (1995). Xu et al. (2003) estimated total economic value of ecosystem services in China whereas Ojeda et al. (2008) found the economic value of environmental services from in-stream flow in Mexico; both studies used the CVM.

Majority of instream water-use valuation studies estimated the total economic value of the in-stream water and associated services rendered to society rather than explicitly the benefit functions showing the changes in benefits at alternative flow levels. Daubert and Young (1981) and Duffield et al. (1992) are among few studies estimated the marginal benefit function for the recreational uses of instream water in the USA. Again, gap exists in measuring the value of several informal and ill-documented yet life supporting instream uses, which predominantly exist in poor and developing countries like Bangladesh and Indonesia.

Fisheries in Bangladesh and fish production from the Teesta

The fisheries sector with its high level of biodiversity plays a significant role to the overall economy of Bangladesh. The sector contributes 60% of the animal protein to the daily diet, 5.24% of country's gross domestic product (GDP), 7% of export earning, and provides livelihood to about 10% of the total population (Oliver, 2002; Ahmad, 2005). Rich in protein, minerals (mainly calcium) and vitamin-A, fishes in Bangladesh are considered a high value food and essential part of the diet (Dugan et al., 2004). Unlike many countries, size of the capture fishery is larger than the culture fishery in Bangladesh. In 2006-2007, capture and culture fisheries account 41% and 39% of the total fish production respectively with the remaining part coming from marine fisheries (BFRSS, 2008).

Department of Fisheries (DoF) under the Ministry of Fisheries and Livestock of the Government of The People's Republic of Bangladesh is solely responsible for providing the fish catch statistics. DoF publishes each year the Bangladesh Fisheries Resources Survey System (BFRSS) yearbook which was initiated in 1983-84 to provide a more systematic and sharper focused fisheries statistics collection services. DoF estimates the fish production using CAS (catch assessment survey) at selected fish landing points or big markets for riverine fisheries and report at district level (BWDB, 1994; Roos et al. 2007). Therefore, this statistics fails to reflect the fish production from a specific river because of either the presence of more than one river in a district or traversing of a river through several districts. In case of Teesta study site, it crosses through Rangpur, Nilphamari and Lalmonir hat districts; however, some other small rivers exist in these districts. Table 6.1 mentions those rivers with some characteristics.

Table 6.1 Rivers passing through Rangpur, Lalmonir Hat and Nilphamari District

District	River	Characteristics/Remark
Rangpur	Teesta	Largest tributary to Brahmaputra-Jamuna River system. Teesta is the accumulated flows of the Karatoya, Atrai and Jamuneshwari rivers
	Karatoya	Four parts: Bogra-Karatoya, Rangpur-Karatoya, Dinajpur-Karatoya and Jamuneshwari-Karatoya. All of them carry very little water now. Downstream name of Dinajpur-Karatoya is Atrai. Falls to Bangali river. Jamuneshwari-Karatoya falls into Bangali. Karatoya was a big river in the past, after 1820's flood its flow declined and now it is a small river.
	Chikli	Small river
	Ghagot	Distributary of Teesta, joins to Brahmaputra; sluggish river, flow is in between 1.50-50 cumec.
	Atrai	Distributary of Teesta and tributary of Brahmaputra.
Lalmonir Hat	Teesta	Large river
	Dharala	Originated from Jaldhaka river. Full during the monsoon but has only knee-deep water in summer. It's a braided river.
	Sarnamati	Small river, almost silted up
	Trimohoni	Small river, presently almost silted up
	Ratnai	Small river, presently almost silted up
	Sati	Small river, presently almost silted up

District	River	Characteristics/Remark
Nilphamari	Teesta	Large river
	Jamuneshwari	Part of Karatoya
	Chikli	Small river
	Dhaigan	Small river

Among all the rivers, Teesta is the main and largest in the region with considerable flow all over the whole year. The other rivers are very small and do not have enough flow, which do not possess significant potential for fish production. Therefore, 70% of fish production of these districts can safely be assumed as originating from Teesta and this assumption is considered based on some discussion with the officers of the DoF field offices while collecting data for the study. Fish catch data for the last twelve fiscal years[2] (1995-96 to 2006-07) of Rangpur, Lalmonir Hat and Nilphamari districts are collected from BFRSS and are presented in Table 6.2.

Table 6.2 Fish production in study site of Teesta

Year	Fish catch (river) in Lalmonir Hat (t)	Fish catch (river) in Nilphamari (t)	Fish catch (river) in Rangpur (t)	Total catch (t)	Catch from Teesta (t)	Value (million Tk)	Value (million US$)
1995-96	111	55	68	234	163.8	20.15	0.284
1996-97	139	67	73	279	195.3	24.01	0.338
1997-98	150	67	53	270	189.0	23.21	0.327
1998-99	150	67	47	264	184.8	22.69	0.320
1999-00	160	107	49	316	221.2	27.31	0.385
2000-01	189	104	46	339	237.3	29.21	0.411
2001-02	203	149	46	398	278.6	34.45	0.485
2002-03	181	157	43	381	266.7	33.07	0.466
2003-04	164	164	114	442	309.4	38.42	0.541
2004-05	155	149	123	427	298.9	37.09	0.522
2005-06	92	126	126	344	240.8	29.99	0.422
2006-07	90	76	105	271	189.7	23.49	0.331
Average	*149*	*107*	*74*	*330*	*231.3*	*28.6*	*0.403*

Note: Value of fish is calculated with average fish price, which is the market price as of May 2008 obtained from DoF, Dhaka. Average fish price for Lalmonir Hat is Tk 120/kg, for Nilphamari is Tk129/kg and for Rangpur is Tk 123.5/kg.
Source: BFRSS issues from 1995-96 to 2006-07.

6.2 Benefit function for fisheries water use

6.2.1 Concepts

Two basic approaches as already mentioned, namely: revealed preference and stated preference are predominantly used to determine economic benefit of environmental goods

[2] Fiscal year is from July to June in Bangladesh. BFRSS uses fiscal year in their analyses.

and services. The former approach involves analyzing relevant market transactions in goods and services whereas the latter one uses survey to identify individual's WTP. Despite having advantages and disadvantages for obtaining economic value using those approaches, most economists prefer to use market data, since such analyses are based on actual behavior rather than hypothetical situation. This study uses actual market benefit of fish production to estimate the instream flow benefits where fishermen income data form the basis for the analysis.

Towards estimating fish production at different flow levels in the river a deep-rooted hydrologic-ecological link is requisite; however, such link is not yet well established in contemporary literature (IWMI, 2005; Arthington et al., 2006). Physical Habitat Simulation system (PHABSIM) developed by Bovee (1982) calculates an index related to the amount of microhabitat available for different life-stages at different flow levels. The method was especially focused at protecting a single species (sport fisheries in North America). Nevertheless, developing a relation between river discharge and all species' habitats, in an integrated form for a complex tropical fishery, with high level of biodiversity using PHABSIM is again challenging to apply.

Instead, the overall habitat can be considered as a proxy to total fish production or catch which can easily be incorporated further into an economic term. It therefore needs a relation between overall habitat and hydrological parameters; however, such a relation is rare in the existing literature. Recently the World Bank (2004) developed a "feeding opportunity index" for the Mekong as a surrogate of fish production and tested for the Cambodian Dai fisheries. This index calculates the productive habitat as the product of area inundated (from water level) and number of inundation days. Baran et al. (2001) modeled water level (in log scale) versus catch relation for the Cambodian Dai fisheries. Such researches provide a background on hydrology and habitat inter-dependency. This paper considers the link among flow (hydrology)-habitat-production for fishery water valuation.

6.2.2 Method

Value of the fish production is considered equal to fishermen income for a certain time period e.g. month or year. A primary survey was conducted to the riparian fishermen to find their income as well as income variation at different flow level in the river. Total numbers of beneficiaries are deduced from demographic information. Total income of the groups in different instream flow levels map out the total instream flow benefit function. First order derivative of the function is the marginal benefit function.

Fishing effort and its associated cost is the fundamental economic component in the biological production of a fishery (Ahmed, 1991; Tietenberg and Lewis, 2009). Each unit of effort is composed of a standard size of labor, gear, vessel, and some other necessary inputs per unit of time. The market prices of these inputs constitute the cost of the effort. Since each unit of effort is capable of catching certain amount of fish, the cost of a particular unit of effort is equivalent to the cost of producing the corresponding amount of fish. Operating costs for fishing are not considered since those are mainly time and labor related and opportunity cost of time and labor can be considered negligible considering the poor socio-economy of the site.

Similar to irrigation water total benefit function, a quadratic function is considered to reflect suitably the usual shape of the fisheries production. Theoretical discussion as well as empirical estimating of instream water value using quadratic function is found in earlier literature, e.g. Daubert and Young (1981), Bishop (1989 cited in Booker and Colby 1995). Moreover, the Tennant (1976) method for assessing environmental flow requirement (such as 50 and 40% of mean annual flow is respectively 'excellent' and 'good' for fish habitat even in high flow season) implicitly indicates that fishes do not need complete virgin flow but the virgin flow is not at all detrimental, which indicates a decreasing marginal utility of flow for fish habitat. Brown (1991) mentioned that this perception can be applied for any time or over an entire year assuming a favorable time distribution of flow. Considering all these arguments, total benefit function is developed as a quadratic function as Equation 3-1. The average income of the respondents for a specific time period and mean discharge for the stated period is used in estimating the benefit functions. Theoretical setup of such model is quite robust; however, empirical validation is really tricky. No literature is found at this moment based on fisheries. This research firstly attempts to validate the model while faced with several challenges such as small sample size, very limited number of data points to carry out the regression analysis, scarcity of resources and secondary information.

6.2.3 Questionnaire survey

A semi-structured primary survey was administered (in local language) to the fishermen in arbitrarily selected 11 out of 26 riparian unions in May and June 2008. Ninety seven fishermen and 23 boatmen were approached randomly where responses were collected from 91 fishermen and 21 boatmen.

The questionnaire was focused on two parts, firstly the dependency of the target groups on river discharge and the variations of their income level with the changes in river flow within a year (open ended), secondly the socio-demographic with few other questions (close ended). Questionnaire is included in Appendix C. An in-depth conversation was held with the individuals for the first question issue and the latter part was structured and focused into specific questions on name, address, age, experience, education, sex, working days per week, family size and fishing mode (individual or group fishing) of the respondents. Instead of analyzing fishing gears, individual or group catching was queried for the fishermen for the simplicity since it was observed at the site that individual catching relates with simpler gears than group catching. For the first part, individuals were asked to respond on their income within a year dividing into as small time slice (e.g. month or season) as possible. Questions were also asked on alternative employment opportunity and corresponding income in case of regular income falls very short. Income value is then made related with corresponding flow for that time slice from secondary source.

6.2.4 Assumptions

Following assumptions are made in establishing the benefit function for fishery water use in the Teesta:

- An intercept indicating zero benefit from a certain flow is an obvious case and is considered in establishing the TB functions. Such intercept is found in earlier researches related to instream water use e.g. Ringler and Cai (2006), Baran et al. (2001) for fishery, Jager and Bevelhimer (2007) for hydropower. This critical flow value for fishery use is taken from the PHABSIM study for the Teesta River by

Bari and Marchand (2006). The study presented the monthly habitat duration curve for the main fish species (Boirali, *Aspidoparia morar*) of the Teesta River and Weighted Usable Area (WUA) against different discharge level. For the 100% habitat exceedence probability (i.e. zero habitat) for the driest month February, the WUA was determined and the corresponding discharge was found about 50 m^3/s. The present study therefore considers an average flow of 50 m^3/s as the critical flow that results zero catch meaning zero benefit for fishermen.

– The average daily income in a season answered by an individual fisherman is considered uniform over the entire season.

– Estimating the total benefit from the fishery sector requires the total number of fishermen working in the study area. However, information related to the number of fishermen living within the study corridor was not readily available. Information based on national demographic survey is used with few underlying assumptions. National demographic survey data (BBS, 2005) provides the number of households engaged in fishery sector at the union (the lowest administrative unit) level. Hence, it is assumed that (i) the fishermen who are working at the Teesta study site live in the riparian unions, (ii) this fishermen are engaged only in capture fishery and (iii) one person from each household is engaged in fishery work. The assumptions seemed valid while comparing the socio-demographic information collected during the field survey.

6.2.5 Sampling for field survey

Based on the assumptions mentioned in the earlier section, total number of fishermen is found. Numbers of household working in fisheries sector from the riparian unions in the study site are reported in Table 6.3.

A total of 920 households are working in fishery sector in the riparian unions. Following the assumptions, the total number of fishermen at the study site is 920.

Sample size estimation

Based on Equation 6-1 (Israel, 2009), the sample size for the primary survey of the fishermen group is estimated.

$$n = \frac{N}{1 + N(e^2)} \qquad (6\text{-}1)$$

Where n is the sample size, N is the population size, and e is the level of precision which is considered as 10% in this case. Calculation based on Equation 6-1 yields the sample size of 90.

Table 6.3 Number of households engaged in fishery work at the study site

District	Upazila	Riparian Union	Total n° of House-Hold	N° Household in fishery
Rangpur	Gangachara	Alam Biditar	7,809	49
		Gangachara	7,383	52
		Gajaghanta	6,238	21
		Kolkanda	5,428	82
		Lakshimari	4,089	31
		Nohali	5,222	75
		Marania	5,865	6
	Kaunia	Kaunia Bala Para	6,886	93
Sub-total Rangpur District				*409*
Nilphamari	Dimla	Jhunagachh Chapani	5,422	32
		Khalisa Chapani	5,279	51
	Jaldhaka	Kaimari	7,957	37
		Saulmari	4,572	9
		Daoabari	2,168	8
Sub-total Nilphamari District				*137*
Lalmonir Hat	Aditmari	Mohiskocha	5,278	6
		Palashi	6,032	57
	Hatibanda	Doabari	3,864	11
		Goddimari	3,596	84
		Patikapara	2,460	9
		Sindurna	2,448	7
	Kaliganj	Bhotemari	4,919	25
		Kakina	5,941	92
	LH Sadar	Gokunda	6,407	42
		Khuniagachh	5,888	25
		Rajpur	3,676	16
Sub-total Lalmonir Hat District				*374*
Total				***920***

Source: BBS, 2005.

6.2.6 Results

In total, 97 fishermen were surveyed from 11 out of 26 riparian unions at the study site, whereas responses were obtained from 91 individuals. Survey unions and individuals were chosen arbitrarily. All the respondents identified three seasons in a year while answering the questions related to income. The seasons are (i) dry or low flow season from December to March, (ii) wet or high flow season from June to September, and (iii) intermediate flow season for the months of April, May, October and November. Even though they identified three seasons, four income values were revealed from the survey. Exception happened for the dry season. To all the respondents dry season is favorable for fishing; however, very dry condition which is occurring in the recent years is not at all good. According to the respondents early dry season (December and January) follows the highest income whereas income falls to the lowest in the middle (February). The late dry season month, March normally follows an income pattern similar to intermediate flow season. Income in the wet season again falls from the intermediate flow season. The average daily income for the seasons in a year of the responded fishermen is tabulated in Table 6.4.

Table 6.4 Average daily income of the respondent fishermen (n=91) at the Teesta study site for different flow seasons

Season	**Months**	**Average daily income in Tk (US$)**	**Average Flow (m^3/s)**
Dry (Low flow)	December and January	207 (2.92)	152
	February	54 (0.76)	88
	March	123 (1.73)	107
Intermediate flow	April and May; October and November	123 (1.73)	466
Wet (High flow)	June – September	73 (1.03)	1,918
Average		115 (1.61)	835

The descriptive statistics of the other variables for the fishermen are presented in Table 6.5 where average age of the fishermen group is found 37 years, average experience of 20 years and the education level of very low – most of them have not completed even the primary school. Average family size is 5 persons. Most of them work seven days a week and prefer to catch fish in group. All of the respondent fishermen are male.

The post barrage period (1991-2006, 16 years) average flow is considered to develop the quadratic benefit function. Respondent fishermen responses and existing literature provided sufficient ground to accept the significant correlation between the respondents' income (surrogate to fish production) and river discharge. However, to find any effect on the response variable 'income' from other factors considered in primary survey, a general linear model (GLM) with repeated measure was employed. GLM repeated measure is used to analyze a response variable which is measured at different times on the same subject. Here, seasonal income data is considered to be measured as a response at different times. The analysis involves both 'within-subjects' factors (incomes at different seasons/time periods) and 'between-subjects' factors (other factors with income). Incomes at different seasons are leveled as 'income' in GLM analysis. Tables C.1 and C.2 in Appendix C present the GLM repeated measure analysis results, which shows that only 'intercept' in the test of Between-subjects Effects and 'income' in the test of Within-Subjects Effects is significant. In the test of Between-subjects Effects 'intercept' corresponds to the 'income' main effect. The interaction with other factors and 'income' is not significant.

The fishermen were asked to acquire their views on the low income at high flow season. Fishes breed and migrate to floodplain in wet season and the local group is aware of the fact. However, the fishermen added that the number of fish catchers increase in the wet season. The modest agricultural activity in the wet season as well as frequent flooding constrain the poor's livelihood and impel them to go for fishing or boating for the livelihood in high flow season. Increased numbers of fishermen and/or low concentration of fish in high flow are the main reasons of low per capita income in the high flow season. Some research (Nehring, 1988 cited in Brown, 1991) found that usually high flow tends to wash the young fishes. Moreover, the inherent meaning of value implies a resource scarcity which is not a considerable issue for Teesta in wet season. Balance of this argument implies that the wet season income of the fishermen might be affected by some other factors rather than flow itself and of less in interest for economic valuation, therefore this income value is dropped in estimating the TB function of fishery water use.

Table 6.5 Descriptive statistics of the fishermen based on questionnaire survey

Variable	**Label**	**Value Label**	**n**	**Average (n=91)**
Respondent Age (year)	1	20-29	15	
	2	30-39	44	37
	3	>=40	32	
Experience (years)	1	10-14	12	
	2	15-20	39	20
	3	>20	40	
Education	0	No edu	29	
	1	<primary	48	2 yrs of schooling
	2	>=primary	14	
Family size (persons)	4		14	
	5		33	5
	6		29	
	7		15	
Working days in a week	6		16	
	7		75	
Individual or group fishing	1	Individual fishing	29	
	2	Group fishing	62	
Sex	1	Female	0	
	2	Male	91	

The TB function is then established with the mean flow for a season/time period and respective average income of the fishermen which has been converted into monthly income. Estimated TB function is given in Equation 6-2 and respective MB function is in Equation 6-3. Figure 6.1 portraits the TB and MB functions for the instream water use, fisheries in the study area. TB and MB values from the equations are values in US$ per month for an individual fisherman.

$$TB_F = -0.002 * flow^2 + 1.344 * flow - 66.784 \quad (6\text{-}2)$$

$$MB_F = -0.005 * flow + 1.344 \quad (6\text{-}3)$$

Since it is considered that 920 fishermen are working at the study site, the aggregated total and marginal benefit for the whole group is estimated and presented in Table 6.6 at different flow levels. At a very low flow such as 50 m^3/s fishermen income practically becomes zero whereas it becomes negative from the model calculation. Around a flow of 290 m^3/s benefit becomes maximum for the fishermen group.

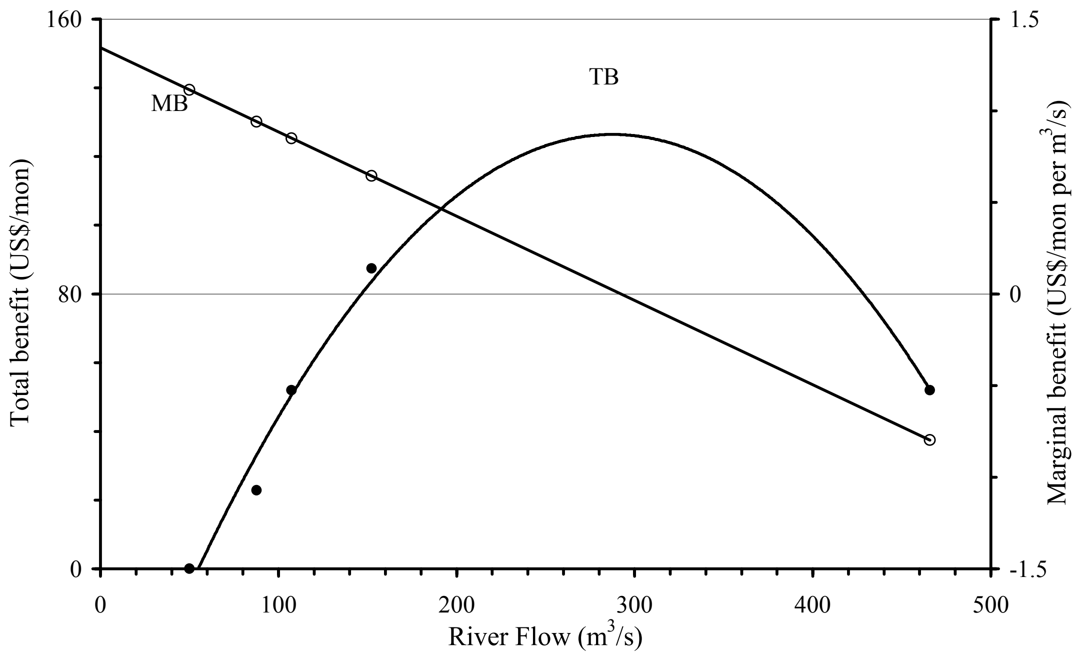

Figure 6.1 Estimated total and marginal benefit function for individual fisherman working in capture fisheries in Teesta

Table 6.6 Total and marginal benefit for the fisheries water use for the Teesta at different flow levels

Flow (m^3/s)	**Individual TB (US$/month)**	**Aggregated TB (US$/month)**	**Individual MB (US$/month per m^3/s)**	**Aggregated MB (US$/month per m^3/s)**
50	-5.33	-4903	1.11	1,025
100	44.63	41,056	0.88	813
150	83.08	76,435	0.65	602
200	110.04	101,233	0.42	390
290	129.58	119,209	0.00	0.00
300	129.45	119,090	-0.04	-33
400	102.86	94,628	-0.50	-456
500	30.27	27,845	-0.96	-879

Note: TB = Total Benefit; MB = Marginal Benefit

The quadratic TB function was found the best fit; however the numbers of observations are few. The negative coefficient of *flow*^{2} in the TB function indicates a downward sloped MB functions and the positive value coefficient for *flow* in the same function indicates an initial positive marginal benefit. Based on the established TB function, 50m^3/s flow generates a negative benefit to the fishermen. The optimum flow for this group is about 290 m^3/s, which is little higher than the mean December flow.

Calculation based on the daily incomes of an individual fisherman for the three seasons gives the annual income for a fisherman is about US$ 581 (Tk 41,250) and the total income for the whole fishermen group becomes US$ 534,507 (Tk 37,950,000).

Considering the average fish price for the study site US$ 1.75 (Tk 124) per kilogram, the total income value indicates an amount of 305 metric tons of fish production per year from the study site stretch of the Teesta. DoF provides the annual fish production the study site of the Teesta River is 231 metric tons which is based on CAS and from landing points as BFRSS follows. The catch value obtained from primary survey includes the whole fishermen catch, which would be higher than CAS based value.

6.3 Benefit function for navigation water use

Navigation is an important mode of transportation especially in a country like Bangladesh having many wide rivers and poorly developed road networks. The sector supports livelihood to a considerable part of population in particular to the riparian poor communities. The main advantage of inland water transport (IWT) is its low operating cost; although subject to slow travel and periodic closure in some cases. In Bangladesh, transport accounts for about 8% of the overall GDP and water-transport generates about 15% of total transport-GDP (World Bank, 2005). However, no data and information on navigational use of Teesta water is available from any organization and secondary source.

6.3.1 Data and methods

For short-run and at-source valuation of water for inland transport, all operating costs subtracted from the estimated gross benefits of the water transport facilities yield the economic benefits for water in navigational use (Gibbons, 1986). The short-run value would be justified due to the high seasonality of navigation, where a negligible marginal value is realized at the high flow period and vice versa. Based on these principles water value for navigation is derived. The boatmen income is considered as the gross benefit from navigation water use.

A semi-structured primary survey was administered (in local language) to the boatmen group along both the banks of the Teesta study site at the same way the fishermen were surveyed with same focus questionnaire and mostly at the same spots. All the boats are manually operated at the site where the operating costs are very minor and the only costs are time and labor related. Opportunity costs of time and labor of the concerned group are regarded negligible in the context of poor socio-economic condition of the study area and considered as zero. Capital cost has not been accounted for since the short run benefit is only concern in this study.

6.3.2 Assumptions

Following assumptions are made in estimating the benefit for navigation water use:

– Based on the responses of the boatmen group, in the driest condition people cross the river by walking and their income goes closer to zero. They further added that such situation occurred in the recent years most likely in February. Considering this, mean flow of the driest month, February (24 m^3/s) for the period of 2001 – 2006 is considered as critical flow when boatmen daily income is considered zero.

– The average daily income in a season answered by an individual boatman is considered uniform over the entire season.

6.3.3 Sampling for field survey

The boundary of the study corridor is kept identical as for fishery sector benefit estimation which is defined earlier in Section 4.1. Since no data and information is available on the total number of boatmen working at the Teesta, The total number of boatmen at the study site is calculated based on a proportionate principle. The study considered first the number of people working in transport sector in each union at the study site which is available from demographic survey data and secondly, the ratio of number of people working in navigation (non-motorized) to number of people working in overall transport sector. BBS (2005) reported the number of people working in the transport sector at the union level as mentioned in Table 6.7.

Bangladesh labor force survey (2008) provided the number of people engaged in transport sector as well as inland water transport separately for mechanized and non-mechanized groups. Since the boats in the study site are mostly non-mechanized, the proportion of the number of people working in inland water transport non-mechanized sector to total number of people working at the transport sector was used in estimating the total number of boatmen in the study area following Equation 6-4.

$$TNB = \sum_{j} PWT_U \ * \frac{PWWT_{NM}}{PWT_C} \tag{6-4}$$

Where, *TNB* is the total number of boatmen, *PWT* indicates the people working at transport sector, $PWWT_{NM}$ is the number of people working in inland water transport non-mechanized sector, *U* is the riparian union, *C* indicates whole country, $j = 1, 2, \ldots, n$ the number of riparian unions. The values of PWT_C and $PWWT_{NM}$ are 2,670,000 and 56,587 respectively.

Using Equation 6-4, the total number of boatmen at the study site is found to be 51. Calculation based on Equation 6-1, the sample size for primary survey came as 34 considering e=10%. However, Israel (2009) mentioned that if the population is small, the sample size can be reduced slightly. This is because a given sample size provides proportionately more information for a small population than for a large population. In such cases, the sample size (n_0) can be adjusted using Equation 6-5 (Israel, 2009).

$$n_0 = \frac{n}{1 + \frac{n-1}{N}} \tag{6-5}$$

Where, n_0 is the adjusted sample size, *n* is the previously calculated sample size, *N* is the population size.

The population size 51 can easily be considered small and in this case using Equation 6-5, the adjusted sample size for the primary survey on the boatmen group appears to be 20.

Table 6.7 Number of people working in transport sector for the Teesta study site

District	**Upazila**	**Riparian Union**	**Total House-Hold**	**HH working in transport**	**People Working in transport**
Rangpur	Gangachara	Alam Biditar	7,809	62	63
		Gangachara	7,383	284	296
		Gajaghanta	6,238	230	258
		Kolkanda	5,428	68	69
		Lakshimari	4,089	94	109
		Nohali	5,222	27	35
		Marania	5,865	51	57
	Kaunia	Kaunia Bala Para	6,886	174	205
Sub-total Rangpur district			*48,920*	*990*	*1,092*
Nilphamari	Dimla	Jhunagachh Chapani	5,422	40	51
		Khalisa Chapani	5,279	44	69
	Jaldhaka	Kaimari	7,957	172	190
		Saulmari	4,572	25	34
		Daoabari	2,168	47	60
Sub-total Nilphamari district			*25,398*	*328*	*404*
Lalmonir Hat	Aditmari	Mohiskocha	5,278	73	95
		Palashi	6,032	162	217
	Hatibanda	Doabari	3,864	54	59
		Goddimari	3,596	99	110
		Patikapara	2,460	21	24
		Sindurna	2,448	93	117
	Kaliganj	Bhotemari	4,919	16	17
		Kakina	5,941	38	51
	LH Sadar	Gokunda	6,407	110	174
		Khuniagachh	5,888	31	31
		Rajpur	3,676	4	8
Sub-total Lalmonir Hat district			*50,509*	*701*	*903*
Total					***2,399***

6.3.4 Results

Twenty three boatmen were approached for the primary survey; however, responses were obtained from 21 individuals. Alike the fishermen group, all the respondent boatmen also told about three seasons (dry, wet and intermediate flow season) in a year while answering the questions related to income. According to the respondents, wet season is the most favorable for boating whereas income becomes the lowest in the dry season. Three income values for the three seasons are recorded for this group. The respondents also added that at severe low flow condition people cross the river by walking. Income falls tremendously in the driest month and in recent years it became zero for some individuals. In this dry period some people shift their work to agriculture field by selling labor. Changing the job mainly occurs for those who operate the boat with two persons for the usual time. In that case one goes for agriculture labor and other remains with the boat because they do not want someone to enter their own area of work. Table 6.8 presents the average daily income of the boatmen group at the study site.

Table 6.8 Average daily income of the respondent boatmen (n=21) at the Teesta study site for different season and respective flow levels

Season	**Months**	**Average Daily Income in Tk (US$)**	**Flow (m^3/s)**
Dry (Low flow)	December – March	68 (0.96)	125
Intermediate flow	April, May, October, November	190 (2.68)	466
Wet (high flow)	June – September	464 (6.54)	1,918
Average		241 (3.40)	835

Descriptive statistics of other variable from the questionnaire are presented in Table 6.9, where the average age of the respondents were found 31 with average experience of 18 years. Education level is very low, average year of schooling was found only one. Average family size was seen five.

Table 6.9 Descriptive statistics for the boatmen based on the questionnaire survey

Variable	**Label**	**Value label**	**n**	**Average (n=21)**
Respondent age (year)	1	20-29	12	
	2	30-39	4	31
	3	>39	5	
Experience (year)	0	<10	4	
	1	10-14	3	18
	2	15-20	8	
	3	>20	6	
Education	0	No education	6	
	1	<Primary	15	1 yr of schooling
	2	>Primary	0	
Family size (persons)	4		7	
	5		8	5
	6		3	
	7		3	
Working days in week	6		4	
	7		17	
Sex	1	Female	0	
	2	Male	21	

Similar to the fishery benefit estimation, the post barrage period 16 years average flow is considered to develop the total benefit function for navigational water use. The core assumption of this research was – income varies with flow within the year. Moreover, to find any effect on the response variable ‘income’ from other factors considered in primary survey, a general linear model (GLM) with repeated measure was employed in the similar manner of fishery benefit estimation. In this case also, incomes at different seasons are leveled as ‘income’ in GLM analysis. Tables C.3 and C.4 in Appendix C present the GLM repeated measure analysis result, which shows that only ‘intercept’ in test of Between-subjects Effects and ‘income’ in test of Within-Subjects Effects is significant. In the test of Between-subjects Effects ‘intercept’ corresponds to the ‘income’ main effect. The interaction with other factors and ‘income’ is not significant.

The approximated quadratic function between individual boatman income and mean flow for the respective income period represents the TB function for the navigation water use (Equation 6-6). Equation 6-7 presents the marginal benefit function of this sectoral water use. Figure 6.2 represents the total and marginal benefit function for the instream water in navigation use. Values from TB and MB functions are in US$ per month for individual boatman.

$$TB_N = -0.00005 * flow^2 + 0.202 * flow - 0.948 \qquad (6\text{-}6)$$

$$MB_N = -0.0001 * flow + 0.202 \qquad (6\text{-}7)$$

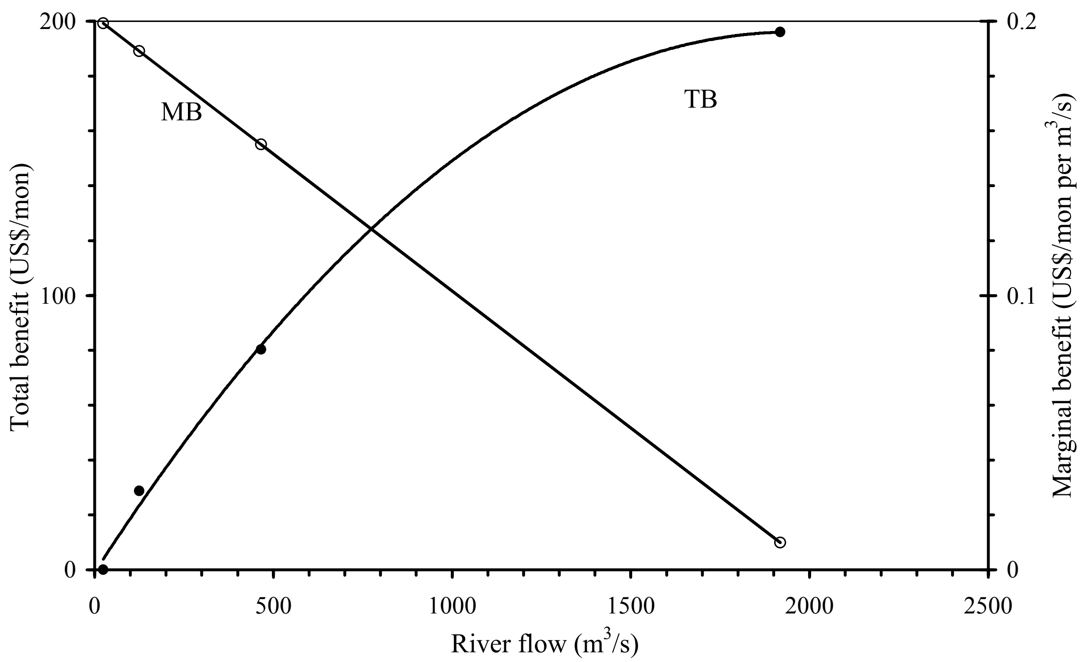

Figure 6.2 Estimated total and marginal benefit function for navigation water use for an individual boatman for the Teesta study site

The maximum benefit generating flow level for the boatmen group is quite high and it occurs in the wet season. The MB function for navigation becomes zero at a flow level about 2000 m^3/s. However, the highest marginal benefit lies at low flow level that calls for especial attention in flow management in this season when the irrigation demand is also very high. The total and marginal benefit of the whole boatmen group (for 51 boatmen) is presented for different flow levels in Table 6.10.

Table 6.10 Total and marginal benefit for the navigation water use from Teesta study site

Flow (m^3/s)	Individual TB (US$/month)	Aggregated TB (US$/month)	Individual MB (US$/month per m^3/s)	Aggregated MB (US$/month per m^3/s)
50	9.01	459	0.20	10.03
100	18.71	954	0.19	9.77
150	28.17	1,437	0.19	9.52
200	37.37	1,906	0.18	9.26
300	55.03	2,807	0.17	8.75
400	71.69	3,656	0.16	8.24
500	87.35	4,455	0.15	7.73
2000	202.25	10,315	0.00	0.00

Marginal value for navigation is lower than the fishery use which demonstrates and confirms the low navigation potential of the study river. The results also imply that navigation at the study river can only support few livelihoods as complementing other activities, while fisheries have large potential for sustaining livelihoods.

6.4 Combined benefit function of instream water uses

The fishery and navigation use of instream water are measured at the same demand point which ask for a combined total benefit function and consequently the demand function. Both the water uses are public and non-rival in nature; therefore a vertical addition of the individual benefit function will generate the combined benefit function as discussed in Section 2.2.3.2. Table 6.11 presents the combined benefits from fishery and navigation use of instream water from the Teesta at some representative flow levels, which gives the TB function for the instream water direct uses for the Teesta. From Table 6.11 it is observed that the maximum benefit generating flow is around 300 m^3/s. The TB and MB functions are given in Equations 6-8 and 6-9, where TB is in US$/month and MB is in US$/month per m^3/s.

Table 6.11 Combined benefits for instream water uses as a function of flow in Teesta

Flow (m^3/s)	Fishery benefit (US$/month)	Navigation benefit (US$/month)	Total benefit (US$/month)
50	-4903	459	-4,444
100	41,056	954	42,010
150	76,435	1,437	77,872
200	101,233	1,906	103,139
300	119,090	2,807	121,897
400	94,628	3,656	98,284
500	27,845	4,455	32,300

$$TB_{instream} = -2.119 * flow^2 + 1246.9 * flow - 61490 \quad (6\text{-}8)$$

$$MB_{instream} = -4.237 * flow + 1246.9 \quad (6\text{-}9)$$

6.5 Discussions and concluding remarks

Low flow season, except severe low flow, for the fishermen and high flow season for the boatmen are economically beneficial. Monthly maximum benefits that can be realized from the fisheries and navigation are about US$ 119,209 at flow 290 m^3/s and US$ 10,315 at flow 2000 m^3/s respectively. Analyses show that fishery benefit is more than ten times higher compare to navigation benefit for the Teesta and fisheries sector therefore controls the instream benefit. Maximum benefits from both sectors are not achieved simultaneously due to the opposite seasonal occurrence of the maximum benefits of individual uses. Nevertheless, the highest marginal benefit for both groups lie at very low flow such as US$ 1,025 (Tk 72,616) per m^3/s per month for fishery (Table 6.6) and US$ 10.03 (Tk 715) per m^3/s per month for navigation (Table 6.10) at a flow level of 50 m^3/s. Such situation demands special attention in flow management for the low flow season when the offstream demand is also very high.

In estimating the fishery benefit, floodplain fishery, which is completely river hydrological phenomenon, is overlooked. Floodplain fishery is more important in monsoon and post-monsoon period mostly related to flood events from high flow season; however, this study is more focused on estimating the benefit and allocating water for the low flow season when all off- and in-stream uses carry high marginal benefit.

The dimension and signaling to economic value of instream uses are markedly at variance with offstream uses. Instream flows are not subjected to the same economic forces as those for out of stream uses (Daubert and Young, 1981). Values of water used as private goods are available in literature, however, literature on water value is rare when it concerns for the uses of water as public goods. Valuation of ecosystem services has been done in many places, but value per unit of water used in fishery or navigation is rare. In a study of fishing activities and distribution of benefits in Bangladesh, Rahman (1989) estimated based on primary survey that the average implied gross value added per fishermen in a 8-hour working day is Tk 51 in dry season from four rivers (Padma, Jumuna, Narissa-padma and Meghna-Nayabhangni); adding average 6% inflation for 20 years over this amount appears to be Tk 165, whereas this study obtained daily income as Tk 207 for the dry season.

Instream water use particularly the fisheries also depends on water quality; however, the water quality aspect is not considered explicitly in this study for the economic valuation. In the study site no major industrial or urban activities exist; water quality issues may therefore only arises from agricultural pollution. However, the return flow path of the Teesta Irrigation Project is looked into, which is found draining to the Jamuna River.

In addition, the study focuses the short term benefits calculated based on only cross-sectional data set on a yearly basis. Time series data for each season can generate more accurate results for the benefit function. However, due to financial and time constraint long term survey could not be carried out as part of the study. Alternatively, fish production information obtained from DoF was not worthy enough because the fish production information is only yearly and districts based.

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7 ENVIRONMENTAL FLOW FOR THE TEESTA RIVER

7.1 Introduction

Increasing concerns over environmental protection and maintaining ecosystem integrity in rivers persuade the water managers to recognize the need of allowing certain amount of flow with an acceptable level of quality in the rivers which is often regarded as environmental flow (EF) (Tharme, 2003). Such flows are now recommended for all the regulated rivers to maintain the river health at least to a specified level. Through mimicking the natural flow regime, EF ensures provisioning of instream flow goods and services that rivers generally provide on which humanity relies in myriad ways.

Owing to its geographic location, rivers in Bangladesh have very high flow in monsoon and low flow in dry season. Historically, water resources and the rivers in Bangladesh have been managed from a supply perspective, particularly putting emphasis on flood management and irrigation development. In contrary, less attention was paid on low flow and environmental flow management. However, with increasing awareness and approbation for maintaining environmental sustainability, focus in water management is being turned into a year round water management (Bari and Marchand, 2006).

First analyzing the long-term flow characteristics of the Teesta, this chapter estimates the environmental water requirements in monthly basis. The results of environmental flow estimations are essentially required in comparing the natural water demand for the river with instream water use demands. In addition the monthly environmental water requirements serve as constraint in the water allocation model.

7.2 Long term flow characteristics of the Teesta

The flow characteristics of the Teesta are analyzed based on last 40 years (1967 – 2006) mean daily flow at Kaunia railway bridge point, which was obtained from BWDB. The data covers both pre and post TIP barrage period. Table 7.1 presents the mean monthly maximum (MMX), mean monthly minimum (MMN) and mean monthly flow (MMF) for three seasons and for five period covering 40 years. Average values of MMX, MMN and MMF of the three seasons for pre- and post barrage period are also calculated and presented. It is evident from Table 7.1 that flow in the post-barrage period has been decreased for all seasons; however, low flow season has been affected more than high and intermediate flow season. It is also evident that in the period of 2000-06, flow has been reduced more in compare to 1991-00 period. This considerable flow reduction in the dry season affects the natural flow regime and jeopardizes instream water uses. Environmental flow assessment is therefore, required to safeguard proper functioning of the river including subsistence uses by the riparian population.

Table 7.1 Long-term flow characteristic of the Teesta at Kaunia (unit: m^3/s)

Flow charac-teristics	Season	Pre-barrage period				Post-barrage period		
		1967-70	1971-80	1981-90	Avg pre-barrage	1991-00	2001-06	Avg post-barrage
MMX	HFS	3,652	3,650	3,704	3,674	3,647	2,259	3,121(85*)
	IFS	1,358	1,075	1,156	1,159	926	770	869(75)
	LFS	161	253	235	228	226	114	187(82)
MMN	HFS	966	957	1,123	1,031	1,271	966	1,155(112)
	IFS	243	350	301	310	275	174	237(77)
	LFS	94	149	149	139	110	50	89(64)
MMF	HFS	1,999	1,896	2,032	1,970	2,140	1,548	1,918(97)
	IFS	481	549	504	519	500	408	466(90)
	LFS	121	175	183	169	152	80	125(74)

Note: MMX – Mean monthly maximum flow; MMN – Mean monthly minimum flow; MMF – Mean monthly flow; HFS – High flow season (June - September); IFS – Intermediate flow season (April, May, October & November) LFS – Low flow season (December – March); *values in parenthesis in last column is the % change in average flow in post-barrage from pre-barrage period

Source: Calculated based on mean daily flow data obtained from BWDB database, 2008

7.3 Environmental flow requirements

Since hydrological methods for EFA correspond to standard setting problems and mainly related to fisheries (Stalnaker et al., 1995), easy to use and require only historical flow records of the stream concern, this method is adopted for Teesta considering the initial stage of research on this river. Mean daily discharge of pre-barrage 24 years period (1967-1990) for Kaunia railway bridge point is used to assess the environmental water requirements. Data is obtained from BWDB database (2008) and reported in Appendix A, Table A.2 Under the category of hydrological methods, three different methods namely: the Tennant method (Tennant, 1976), the Flow Duration Curve (FDC) method and the Range of Variability Approach (RVA) (Richter et al., 1997) are used in the study. Environmental flow assessment using Tennant method provides flow requirements as percentage of mean annual flow, FDC prescribes a flow based on a specified exceedence probability and for RVA corresponds with a target (e.g. +/- 1SD) from mean the flows for each month.

7.3.1 Tennant method

Based on various condition of habitat quality, Tennant method proposes eight flow classes as environmental flow requirements for two different seasons, namely: high and low flow season and the eight classes of flow are based on mean annual flow (MAF). For the case of Teesta, the MAF at Kaunia is 886 m^3/s for the pre-barrage period (1967 – 1990), on which further calculations are based on. Results from Tennant method analysis are tabulated in Table 7.2. The first column lists the required percentage of mean annual flow (MAF) and their qualitative criterion of fish habitat as defined by Tennant for high flow season and second column presents the flow values that are calculated by multiplying the Tennant percentages and MAF value. Following next columns present the same calculations for the low flow season.

Table 7.2 Environmental flow requirements for the Teesta based on Tennant method

High flow season		Low flow season	
% of MAF	**Flow (m^3/s)**	**% of MAF**	**Flow (m^3/s)**
200% Flushing flow	1,772	200% Flushing flow	1,772
60-100% Optimum range	532 – 886	60-100% Optimum range	532 – 886
60% Outstanding	532	40% Outstanding	354
50% Excellent	443	30% Excellent	266
40% Good	354	20% Good	177
30% Fair or degrading	266	10% Fair or degrading	89
10% Poor	89	10% Poor	89
<10% Severe degradation	<89	<10% Severe degradation	<89

Note: MAF = mean annual flow, based on the pre-barrage period (1967 – 1990)

7.3.2 FDC method

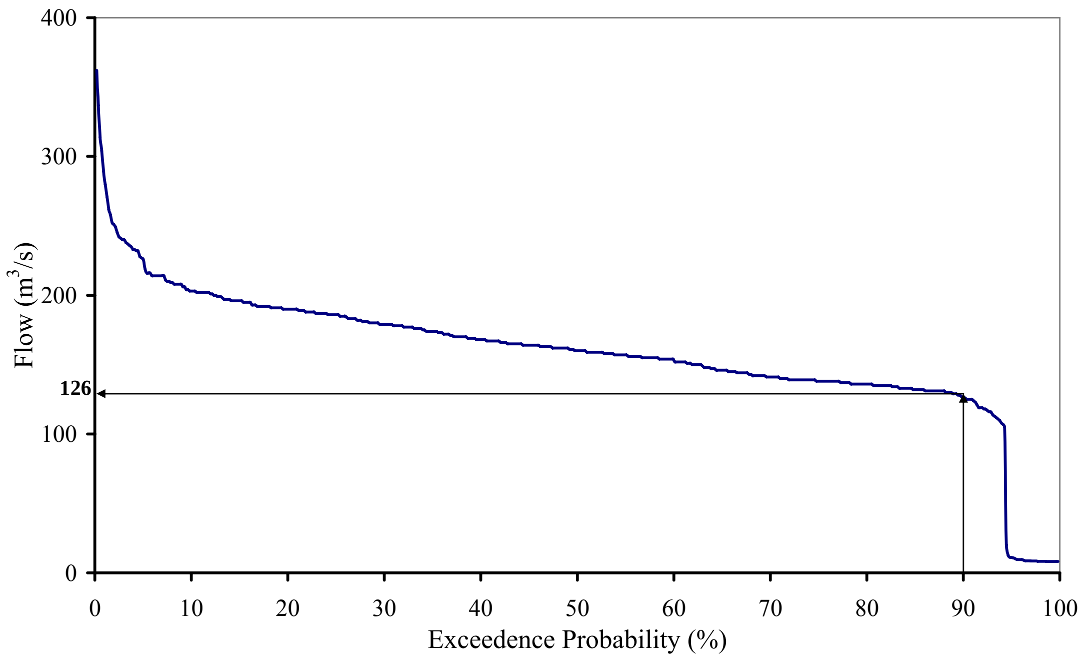
Twelve monthly FDC are first developed based on the daily mean flow at Kaunia for the period of 1967 – 1990. Environmental flow is considered from the monthly FDC, which is considered as 50th percentile for the high and intermediate flow season and 90th percentile for the low flow season. Since the level of protection is implicit in the magnitude of percentage, different exceedence probabilities have been used in specifying EF. However, 90th percentile as minimum flow is practiced in Brazil, Canada and UK (Tharme, 2003) and 50th percentile for the high and intermediate flow season and 90th percentile for the low flow season is used by Bari and Marchand (2006) in an earlier EF assessment study in Bangladesh. Table 7.3 presents the seasonal EF requirements for the Teesta at Kaunia. Results show that 108 – 151 m^3/s flow is necessary to provide as EF for the low flow season. Figure 7.1 (a) and (b) shows representative FDC for the month of January and February. Both of the months are in dry season and 90th percentile flow is considered as EF. All other monthly flow duration curves are documented in Appendix D, Figures D.1, D2 and D3.

Table 7.3 FDC based environmental flow requirements for the Teesta based on mean daily flow at Kaunia for pre-barrage period (1967 – 1990)

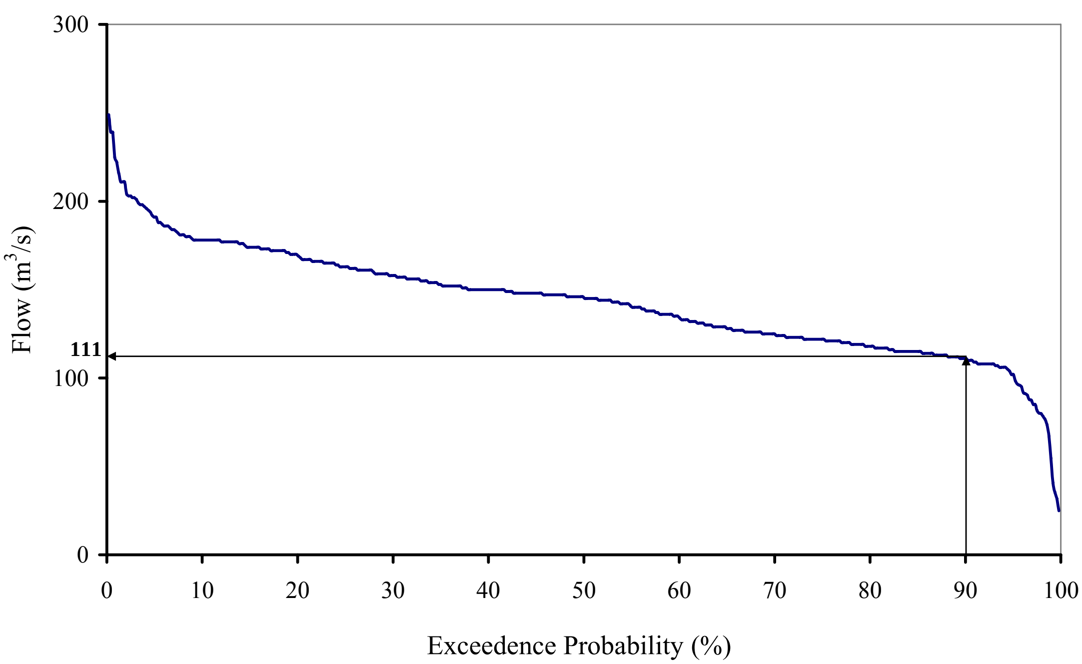
Flow Season (months)	Percentile value	Flow (m^3/s)
High flow (Jun – Sep)	50th	1,280 – 2,180
Intermediate flow (Apr, May, Oct, Nov)	50th	228 – 803
Low flow (Dec - Mar)	90th	108 – 151

7.3.3 RVA method

The Range of Variability Approach uses statistics of time series of the flows and suggests for a flow target to protect the natural ecosystem. The method takes account 32 hydrologic parameters as mentioned in Table 2.6 and gives analytical output of hydrologic alteration for any flow modification. The RVA method is therefore suitable for assessing the impact of any existing dam or diversion scheme. This method is applied for Teesta where last 40 years (1967 – 2006) daily discharge data at Kaunia is used. Year 1990 is taken as the end of pre-impact period. The method provides a flow target with the primary objective of protecting natural ecosystem by resembling the natural flow regime. Mean monthly flow for the pre-barrage and post-barrage period with the RVA targets are reported in Table 7.4. RVA targets are set at +/- 1 standard deviation (SD), in setting such target it is implicitly assumed that values within these limits from the mean are not expected to have significant impact on stream ecology.



(a) January



(b) February

Figure 7.1 FDC and required EF for the month of January and February for the Teesta at Kaunia

Since the research is concern on monthly flows and its allocation in a monthly time step, RVA boundaries and hydrologic alteration for 12 months (12 parameters) are analyzed instead of analyzing 32 RVA parameters. Table 7.4 presents mean monthly flows for post-barrage periods and compares the values with high and low RVA targets as obtained from RVA analysis. It becomes evident from Table 7.4 that the flows in the post-barrage dry season became affected and in particular for the period of 2001-06 the impact is very high.

Table 7.4 RVA targets (m^3/s) and mean monthly flows (m^3/s) for the Teesta at Kaunia

Season	Months	High RVA Target	Low RVA target	MMF for pre-barrage period 1967-1990	MMF for post-barrage period	
					1991-2000	2001-2006
Low flow	December	279	149	214	199	200
	January	200	118	159	144	40
	February	168	119	143	126	24
	March	190	134	162	138	57
Intermediate flow	April	315	199	257	235	146
	May	675	413	544	535	335
High flow	June	1,847	1,013	1,430	1,497	1,182
	July	2,875	2,015	2,445	2,596	1,978
	August	2,757	1,583	2,170	2,527	1,669
	September	2,207	1,466	1,836	1,938	1,362
Intermediate flow	October	1,278	602	940	898	864
	November	460	250	355	333	289

Note: MMF = Mean monthly flow

In RVA analysis, the full range of pre-impact data for each IHA parameter is divided into three categories, namely: high, middle and low. The boundaries between the categories are based on RVA target setting, which is +/-1 SD in this study. IHA software then computes the expected frequency with which the "post-impact" values of the IHA parameters should fall within each category (expected frequency). The program then computes the actual frequency with which the "post-impact" values of IHA parameters fell within each of three categories (observed frequency). Hydrologic alteration is then calculated using Equation 7-1 separately for the three categories. Table 7.5 presents the hydrologic alteration of the Teesta at Kaunia for the 12 IHA parameters related to mean monthly flow. A positive hydrologic alteration value means that the frequency of values in the category has increased from the pre-impact to the post-impact period, while a negative value indicates that the frequency of values has decreased.

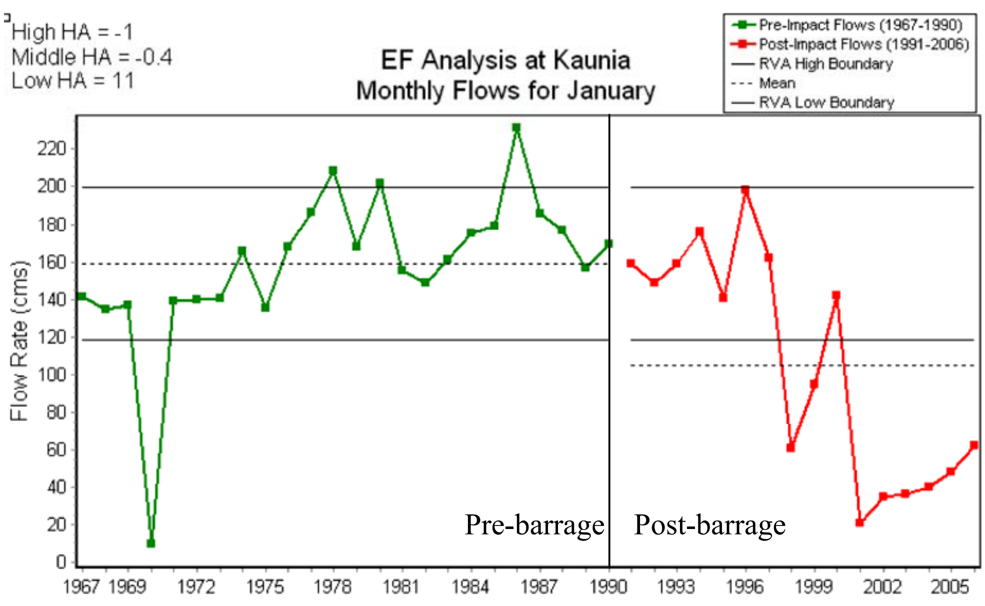
$$HA = \frac{observed\ frequency - expected\ frequency}{expected\ frequency} \qquad (7\text{-}1)$$

where, HA is the hydrologic alteration.

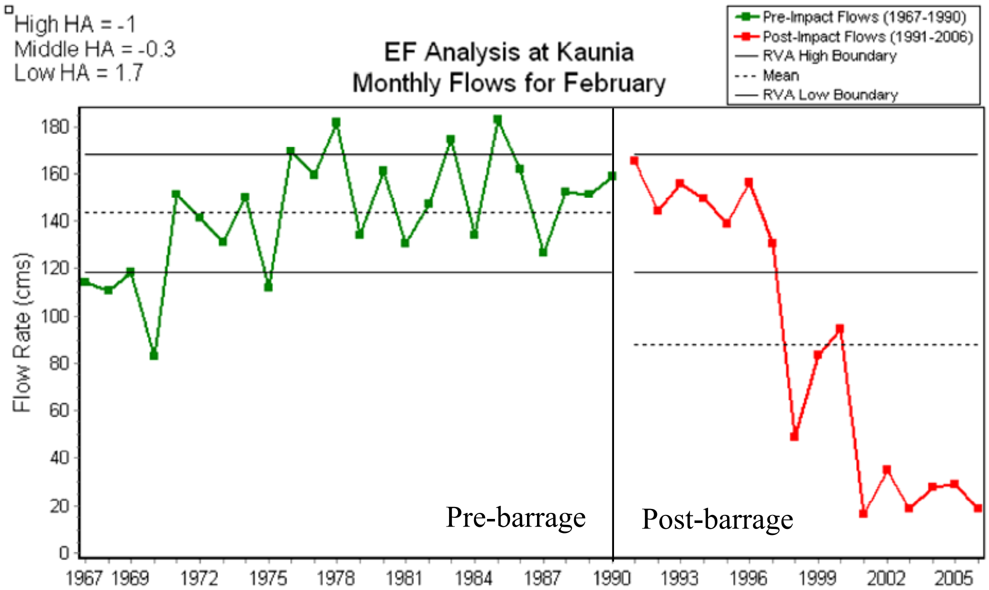
From Table 7.5 it is observed that hydrologic alteration for the low category for each month has a positive value except the month of June, which clearly shows that mean monthly flow has fallen in a high number of frequencies in the post-barrage period in compare to pre-barrage period. Whereas for the middle category except June all months have negative alteration values and dry season months also have negative alteration for high RVA category. Mean monthly flows for January and February are also shown in Figure 7.2 (a) and (b) with the three RVA categories and hydrologic alteration values. Mean monthly flow with RVA targets for the other months are reported in Appendix D, Figure D.4.

Table 7.5 Monthly hydrologic alteration values for the Teesta at Kaunia

Season	**Month**	**Middle RVA Category**			**High RVA Category**			**Low RVA Category**		
		Exp.	**Obs.**	**Alter.**	**Exp.**	**Obs.**	**Alter.**	**Exp.**	**Obs.**	**Alter.**
Low flow	December	13.33	10	-0.25	2.00	2	0.00	0.67	4	5.00
	January	13.33	8	-0.40	2.00	0	-1.00	0.67	8	11.00
	February	10.00	7	-0.30	2.67	0	-1.00	3.33	9	1.70
	March	10.67	7	-0.34	2.00	0	-1.00	3.33	9	1.70
Intermediate flow	April	9.33	10	0.07	3.33	0	-1.00	3.33	6	0.80
	May	12.00	6	-0.50	2.00	2	0.00	2.00	8	3.00
High flow	June	10.67	11	0.03	2.67	3	0.13	2.67	2	-0.25
	July	10.67	8	-0.25	2.67	3	0.13	2.67	5	0.88
	August	12.67	10	-0.21	2.00	3	0.50	1.33	3	1.25
	September	11.33	7	-0.38	2.67	3	0.13	2.00	6	2.00
Intermediate flow	October	11.33	13	0.15	2.67	1	-0.63	2.00	2	0.00
	November	14.00	12	-0.14	1.33	1	-0.25	0.67	3	3.50



(a) January



(b) February

Figure 7.2 Mean monthly flow with RVA targets at Kaunia Point of the Teesta River for the months of (a) January and (b) February

7.3.4 Setting environmental flows

The environmental flow requirements are estimated using the Tennant method, FDC method and RVA method and the results are presented in Tables 7.2, 7.3 and 7.4. Reasonable consistency is observed among the EF assessment results obtained from the three different methods. FDC method recommends a flow range of 108 – 151 m^3/s for the low flow season which is in between 'Fair or degrading' to 'Good' status according to Tennant method as well as it complies with (lower) RVA targets for the months of December to March (dry season). A PHABSIM study on EF assessment for the Teesta carried out by Bari and Marchand (2006) showed that for 75% habitat exceedence probability (which is reasonably a lower limit of the habitat and around the inflection point); the required flow for the dry season should be in the range of 115 – 280 m^3/s. Assessment of EF from PHABSIM study is within the RVA target and also in the range of FDC suggested EF as well as it shows a 'fair or degrading' to 'good' status as estimated by Tennant.

Managing the flow in the low flow season is the main concern and a considerable flow reduction is observed particularly in low flow season in the post-barrage period. In the period of 2001-2006 the flow reduction is extremely high, mean monthly flow of the low flow season is observed only 80 m^3/s (Table 7.1) which indicates severe degradation according to Tennant method. The individual mean monthly flow for January, February and March for the above period (Table 7.4 last column) is far beyond the least recommended level of 89 m^3/s by the Tennant method. Considering the analyses using three different hydrological methods, low RVA target is used further in optimization model as the required flow for the Teesta River at the downstream point, Kaunia since it defines a specific value for each month. This low RVA boundary is used as the constraint in the water allocation model when environmental protection is considered to be maintained.

However, the lower boundary of the RVA analysis for the dry season months does not reach up to the level when the instream use benefit becomes the maximum. Maximum fishery benefit is achieved at 290 m^3/s flow (Table 6.6) and for navigation the maximum benefit lies at a flow of 2000 m^3/s (Table 6.10), which demands a higher flow in the river. On the other hand, basin managers might not feel much interest to maintain such a lower limit at the downstream point since it will reduce flow for the irrigation. In such a situation more dynamic decision in terms of EF provisioning is necessary to realize the maximum instream use benefits by providing more instream water or might be keeping environment happy to a little extent by reducing instream flow and maximize irrigation benefit.

For managing such situation, two more analyses are performed in RVA analysis taking +/- 0.5 and +/- 1.5 SD. The former case results a higher RVA boundary whereas the latter case produces a lower boundary for EF. Results are reported for these two analyses in Table 7.6. Sensitivity of the optimization model due to EF provisioning would be tested using these results.

Table 7.6 Results of monthly low RVA target values analyzing for +/- 0.5 SD, +/-1 SD and +/-1.5 SD RVA target for the Teesta at Kaunia

Season	**Months**	**Low RVA Target using +/- 0.5 SD**	**Low RVA Target using +/- 1.0 SD**	**Low RVA Target using +/- 1.5 SD**
Low flow	December	181	149	116
	January	139	118	98
	February	131	119	106
	March	148	134	120
Intermediate flow	April	228	199	169
	May	478	413	347
High flow	June	1,221	1,013	804
	July	2,230	2,015	1,800
	August	1,877	1,583	1,777
	September	1,651	1,466	1,528
Intermediate flow	October	771	602	433
	November	303	250	198

8 OPTIMAL WATER ALLOCATION IN THE TEESTA RIVER

8.1 Introduction

The uneven distribution of rainfall and hence river flow (i.e. water supply) as well as water demands in spatial and temporal scales make the water resources management often complicated. In addition, the ever increasing freshwater demands from growing population, urbanization and industrialization and various limits over supply augmentation frequently result in conflicts between and among users with the scarce water resources at many places. Besides the offstream demands, increasing awareness and approbation for environmental water requirements makes the situation more critical. Often conflicts are observed between human (offstream uses) and nature (environmental flow). Hence, efficient and acceptable water allocations not only among offstream users but also between in- and off-stream sectors are becoming central in managing the water resources effectively and efficiently.

Allocation of water would be efficient while the value that water resources provide to society is maximized. Economics offers methods in appraising efficiency and equity while allocating water to the competing sectors. Economics helps water professionals in shifting the concept of a discrete volumetric demand to a demand-function. The inherent intricacy of the water system with many interdependent components and the interactions between water and economy are suitably be captured in hydro-economic models where relevant hydrology and economic 'laws' of supply and demand are linked together. The individual demand function of each water use determines the water allocation in hydro-economic modeling. Hydro-economic models (HEM) are characterized as economic optimization model embedded with hydrologic simulation to allocate water optimally and efficiently in a spatio-temporal scale. Incorporating the economic aspects such models provide important insight in policy formulation (Ward and Pulido-Velazquez, 2008).

In general, in designing HEM, water resources systems are modeled as network of storage and junction nodes. The conveyance links join the junctions and represent the river reaches, canal, pipelines etc. The demand sites that incur a cost or benefit from water use are presented as node. Economic benefit functions for water uses (i.e. at each node) provide the economic information to the model for a particular time-step. Details on hydro-economic modeling are provided in Section 2.4.

An evaluation of the currently available generalized modeling system to set up an HEM for the study basin is carried out based on a number of criteria as presented in Table 2.8. Evaluation criteria include: design of HEM, major problem addressed, addressing the environmental water need, time-step, application to basin and availability of the model in the public domain. Accordingly, the Aquarius model (Diaz et al., 1997) is selected for solving the optimal water allocation problem for the Teesta site. Aquarius is an open wired, Microsoft PC based model which considers:

– marginal benefit function as the allocation criterion,
– monthly time step for water allocation,

- instream water uses,
- modular type HEM modeling.

8.2 Water allocation at the Teesta study site using HEM

8.2.1 Objective function

Since water supply may become limited at any stage within a year, water allocation based on seasonal or yearly water quota constraints in the earlier allocation models (e.g. Mahan, 1997) does not reflect the actual scenario of solution to water allocation problem. At present, HEMs are practiced to allocate water optimally among the stages within a season or year, e.g. Rosegrant et al. (2000), Ringler (2001), Cai et al (2003). These researches worked on economic optimal water allocation considering a monthly time step. The current research formulates a hydro-economic model for optimal water allocation in a river basin based on derived benefit functions for several demand sites. Equation 8-1 represents the objective function of the hydro-economic model.

$$\max\left(\sum_{n}\sum_{t} B_{nt} : X \in \Omega\right) \qquad (8\text{-}1)$$

Where, B_{nt} is the benefit (consumer surplus) for demand node, n during time period, t and $X \in \Omega$ presents the set of constraints of the model as mentioned in Equation 3-9.

In this study, the marginal benefit functions for the water use sectors are derived externally and then are incorporated into the optimization model, which is solved using Aquarius modeling software. Detailed description of Aquarius is provided in Section 3.4.2.

8.2.2 Teesta river study site network

Two water users namely: irrigation water supply for the TIP as offstream and instream capture fishery and navigation as the instream users are considered for optimal water allocation at the Teesta river study site. There is one flow measuring station (Dalia) above the irrigation diversion and the other flow measuring station is located at the downstream point Kaunia. The river network is schematized in Figure 8.1. Instream demand site is considered at the point of flow measurement station at the downstream.

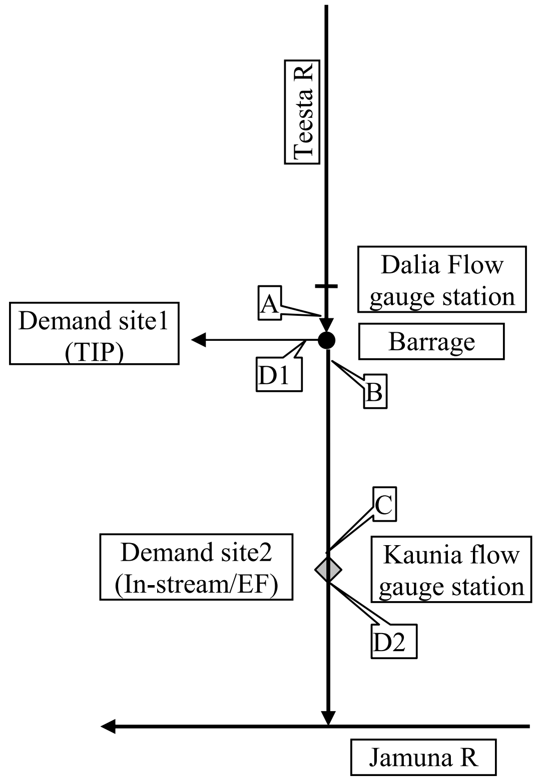


Figure 8.1 Schematic of the Teesta River Network at study site

8.2.3 Physical and economic data for 'Aquarius'

8.2.3.1 Physical data

- Dalia inflow: observed flow at Dalia (upstream of the barrage) for last 16 years of the post-barrage period is entered as input for inflow, named as 'Dalia inflow'.
- Local flow in between Dalia and Kaunia: in general, at the downstream point, Kaunia the flow is higher than the remaining flow after irrigation diversion. The difference between the observed flow at Kaunia and the remaining flow after irrigation diversion is given as separate input with the name of 'Kaunia local flow' to satisfy the hydrological flow balance.
- Irrigation demand site, TIP: minimum irrigation demand is considered as zero and maximum irrigation demand is taken from the monthly irrigation demand as calculated in Table 5.9. Operation constraint is considered as maximum flow, which means the diversion for irrigation would occur up to the maximum irrigation demand.
- Instream demand site: maximum and minimum flow is entered as calculated in low and high RVA target (Table 7.4). In case of environmental flow (EF) demand is considered in water allocation, minimum flows (i.e. the low RVA target) for each month are considered as the operational constraint.

8.2.3.2 Economic data

Economic data input involves in defining the demand functions for each water use through giving input of the necessary coefficient values to specify the demand curve.

- Irrigation demand site, TIP: two options are available in defining irrigation water use demand curve in Aquarius, namely: exponential decaying price and constant price. However, the established demand function (or marginal benefit function, as given in Table 5.13 and Figure 5.4) for TIP is linear. The linear demand curve is converted into a fitted flat exponential curve (discussed and shown in Appendix E, Table E.1 and Figure E.2) and the coefficient values are used in the model. Coefficient values for *a* and *b* are respectively 46,000 and 490 where a and b is as defined in Aquarius.

- Instream demand site: options for defining instream demand function in Aquarius are either linear or constant price function. The established marginal benefit function for instream uses is linear and the coefficient values are used directly to the model. Coefficient values for *a* and *b* are respectively 495 and 0.66 where *a* and *b* is as defined in Aquarius (discussed in Appendix E).

8.2.4 Solving the water allocation problem

- Selecting optimization technique: Aquarius uses Sequential Quadratic Programming (SQP). Two groups of parameters value are required, namely: sequence parameter (that control sequential approximation) and Accuracy parameters (that control the accuracy of the calculations). Values for sequence and accuracy parameters are used as suggested in the Aquarius manual to solve the optimal water allocation problem for the Teesta.
- Model boundary and verification of the output: Only a certain reach of the Teesta is considered for the study, which is bounded by the TIP barrage at the upstream to Kaunia Railway Bridge at the down stream. Flows are measured both at these two points, which are obtained from BWDB database. These two gauging stations are the upstream and downstream boundary for the model. The model is verified with the monthly flows at downstream (Kaunia) point for 16 years (1991 - 2006) post barrage period with the mean monthly observed flows at the same point for the same time period. The model output and observed discharge is compared (shown in Figure E.3 in Appendix E), which fits with an r^2 value of 0.97.

8.3 Results – optimization model

The model is first run for the existing operation policy, which refers to maximization of economic benefit without any constraint. Monthly irrigation demands are the only operational constraints (maximum diversion) and no EF constraint is considered. This scenario is termed as baseline scenario (S0, Case-I). The baseline scenario is also run with the constraints of monthly EF requirements, which is termed as scenario S0, Case-II.

Several alternative scenarios (as mentioned in Table 8.1) are also run and the sensitivity of the model is carried out. For each individual alternative scenario, two cases are considered, namely; Case-I: economic efficiency (without EF constraint meaning that water is allocated to maximize overall benefit) and Case-II: environmental protection (i.e. ensuring environmental flow demand at the downstream).

Table 8.1 Scenarios considered for optimal water allocation in Teesta

Scenario	Description	
S0		Baseline (existing operation policy)
S1		Change in flow level
	S1-a	Dry year flow (25% lower flow than the average year flow)
	S1-b	Wet year flow (25% higher flow than the average year flow)
S2		Improvement of irrigation efficiency
	S2-a	Irrigation efficiency 0.5
	S2-b	Irrigation efficiency 0.6
S3		Change of irrigable area
	S3-a	25% decrease in irrigated area
	S3-b	25% increase in irrigated area
S4		Change in EF level
	S4-a	S4-a: increased level of EF based on RVA target +/- 0.5 SD
	S4-b	S4-b: decreased level of EF based on RVA target +/- 1.5 SD

The minimum EF values in the baseline scenario (S0, Case-II) are considered as the lower RVA boundary analyzed with +/- 1 SD, which does not reach to the maximum instream water-use benefit level. A higher flow level is therefore necessary to maximize the instream water use benefits. Again, ensuring EF results huge benefit reduction in irrigation sector, which might act negatively on providing EF where basin managers might look for a lower EF values. Keeping such issues in mind, scenario S4 is considered with two cases of higher and lower EF levels. Environmental flow values for these two cases are reported in Table 7.6.

8.3.1 Baseline optimal solution

In the baseline, mean monthly flows for the post-barrage 16 years are considered as the inflow to the system and benefits are calculated for mean flow for the above mentioned 16 years flow. Irrigation withdrawal capacity is fully utilized in the scenario S0, Case-I. Table 8.2 presents the monthly water allocation as well as the flow balance for the study site river system. The first and last months of irrigation season (i.e. November and April) have excess of inflow and other months fall in deficit to satisfy irrigation demands. Total satisfied irrigation demand is 1,637 mm out of 1890 mm. It is observed that Monthly EF requirements are not fulfilled for the months of January till March in this case. Mean monthly flow at Kaunia as obtained from the model for the analyzed period 16 years and the lower RVA target is shown in Figure 8.2.

Table 8.2 Monthly flow allocation and flow balance for all the demand sites of the Teesta for the scenario S0, Case-I (Unit: m^3/s)

Month	Demand site-1 (TIP)				Local flow between B to C	Demand site-2 (Instream/EF demand)	
	Flow at A	Demand for TIP	Diversion D1	Flow at B		Flow at C	Flow at D2
Irrigation season (November - April)							
Nov	312	166	166	146	170	316	316
Dec	167	194	167	0	178	178	178
Jan	113	134	113	0	81	82	82
Feb	98	161	98	0	88	88	88
Mar	124	128	124	0	76	76	76
Apr	224	29	29	196	39	234	234
Average	173	135	116	57	105	162	162
Total (10^6 m^3) (mm)		2,105 (1,890)	1,807 (1,637)				
Non irrigation season (May - October)							
May	535	0	0	535	49	584	584
Jun	1,409	0	0	1,409	162	1,572	1,572
Jul	1,804	0	0	1,804	647	2,451	2,451
Aug	1,972	0	0	1,972	475	2,447	2,447
Sep	1,580	0	0	1,580	286	1,866	1,866
Oct	716	0	0	716	166	882	882
Average	1,336	0	0	1,336	298	1,634	1,634

Note: A, B, C, D1 and D2 are the locations as shown in Figure 8.1

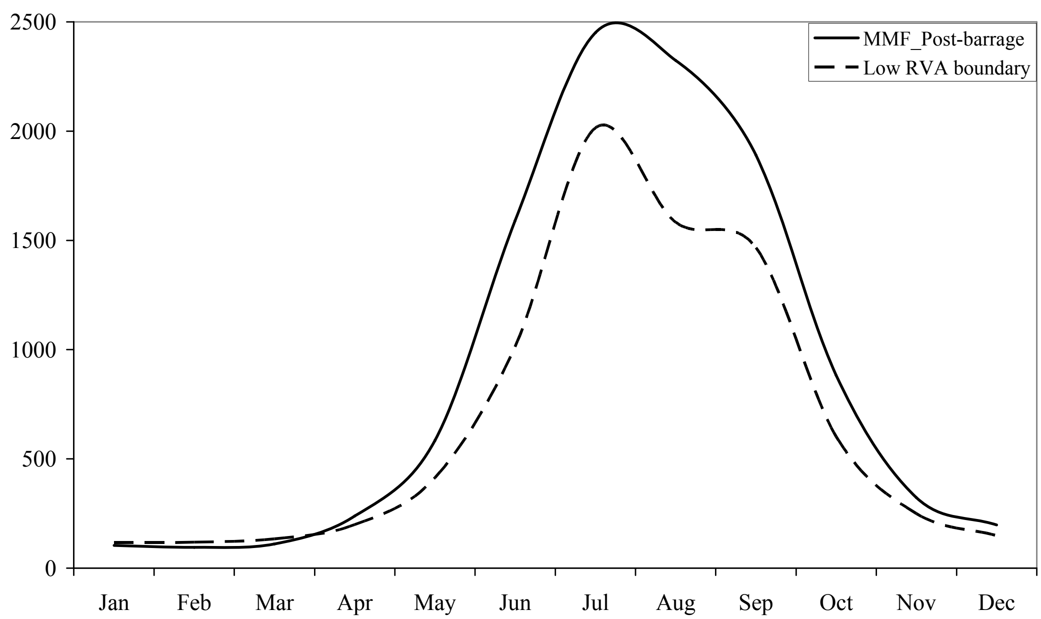


Figure 8.2 Mean monthly flow (MMF) at Kaunia (D2) as obtained from model and the lower RVA boundary (*Note*: Location, D2 is as shown in Figure 8.1)

In this baseline scenario, total irrigation benefit of US$ 43.242 million (Tk 3,070.2 million) and instream water use benefit of US$ 0.588 million (Tk 41.8 million) composed of the total benefit of US$ 43.830 million (Tk 3,111.9 million) for the Teesta study site river system. Maximum irrigation benefit can reach up to US$ 49.587 million (Tk 3,520.7 million as shown in Table 5.11) if the full irrigation supply is secured from the river. In case of less flow is available for diversion to TIP, farmers in general use groundwater to irrigate their field to meet the irrigation demand. In such situation, using Equation 5-6(a) the irrigation benefit is estimated, which yields the off-stream benefit of US$ 48.210 million for the baseline scenario. If in case farmers opt for reduced crop coverage to have full irrigation with this less flow, the benefit would be US$ 42.97 million (based on Equation 5-6(b)).

Since, this baseline scenario does not satisfy EF requirements at the downstream as depicted in Figure 8.2, the baseline scenario is again run with the constraint of satisfying the minimum instream flow as obtained from RVA analysis (taking RVA boundary +/- 1 SD), which is termed as Scenario S0, Case-II. For this run, the water allocation and flow balances are presented in Table 8.3.

Table 8.3 Monthly flow allocation and flow balance for all the demand sites of the Teesta for the scenario S0, Case-II (Unit: m^3/s)

Month	**Demand site-1 (TIP)**				**Local flow between B to C**	**Demand site-2 (Instream/EF demand)**		
	Flow at A	**Demand for TIP**	**Diversion D1**	**Flow at B**		**Flow at C**	**Demand***	**Flow at D2**
Irrigation season (November - April)								
Nov	312	166	166	146	170	316	250	316
Dec	167	194	167	0	178	178	149	178
Jan	113	134	76	37	81	118	118	118
Feb	98	161	67	31	88	119	119	119
Mar	124	128	66	58	76	133	134	134
Apr	224	29	29	196	39	234	199	234
Average	173	135	95	78	105	183	162	183
Total (10^6 m^3)		2,105	1,480					
(mm)		(1,890)	(1,325)					
Non irrigation season (May - October)								
May	535	0	0	535	49	584	413	584
Jun	1,409	0	0	1,409	162	1,572	1,013	1,571
Jul	1,804	0	0	1,804	647	2,451	2,015	2,451
Aug	1,972	0	0	1,972	475	2,447	1,583	2,447
Sep	1,580	0	0	1,580	286	1,866	1,466	1,866
Oct	716	0	0	716	166	882	602	882
Average	1,336	0	0	1,336	298	1,634	1,182	1,634

Note: *This demand is the EF constraint in the model; A, B, C, D1 and D2 are as shown in Figure 8.1

Assuring environmental flow causes a net reduction in benefit by US$ 9.247 million (Tk 656.5 million) that comprises US$ 9.349 million (Tk 663.8 million) reduction from irrigation sector and US$ 0.102 million (Tk 7.2 million) increase from instream uses (Table 8.4). ensuring EF results decrease in irrigation benefit by 21.33%, whereas increase in instream benefits by 0.23% on the basis of the total benefit as estimated for S0 Case-I. However, it is worth noting that the highest instream benefit lies around a flow of 300 m^3/s (as shown in Table 6.11) whereas low RVA target prescribes a flow of 120 – 150 m^3/s in the dry season (as presented in Table 7.4), which indicates that increase in instream flow level will increase instream water-use benefits.

Table 8.4 Comparison of off- and in-stream sectoral benefit (10^6 US$) for Case-I and Case-II in baseline scenario (S0)

Sector	Benefit in Case-I	Benefit in Case-II	Change in benefit in Case-II from Case-I
Offstream (TIP)	43.242 (98.66)	33.893 (77.33)	– 9.349
Instream (capture fishery & Navigation)	0.588 (1.34)	0.690 (1.57)	+0.102
Total benefit	43.830 (100.00)	34.583 (78.90)	– 9.247

Note: Number in parenthesis is the percentage to total benefit as obtained from S0 Case-I

8.3.2 Alternative runs – sensitivity analysis

The optimization model is run for all the above mentioned scenarios (S1 – S4) with Cases I and II. Optimal allocations of water in between offstream and instream sectors are estimated and presented for two seasons namely irrigation season (November to April) and non-irrigation season (May to October) in Table 8.5. In baseline scenario, S0 Case-I, 85% of the irrigation demand is met, whereas in the same scenario with Case-II the level of meeting demand comes down to 70%. In wet year scenario and in the scenario of improved irrigation efficiency the level of meeting irrigation demand may rises to as much as 96% and 98% when EF is not considered.

Table 8.5 Allocated flow (m^3/s) to the sectors for different scenarios and cases

Scenario	Case-I				Case-II			
	For the months of Nov-Apr		For the months of May-Oct		For the months of Nov-Apr		For the months of May-Oct	
	Offstream	Instream	Offstream	Instream	Offstream	Instream	Offstream	Instream
S0	116 (85)	162	0	1,634	95 (70)	183	0	1,634
S1-a	93 (68)	115	0	1,215	47 (35)	161	0	1,215
S1-b	130 (96)	221	0	2,025	125 (92)	226	0	2,025
S2-a	104 (96)	176	0	1,634	87 (81)	193	0	1,634
S2-b	89 (98)	191	0	1,634	79 (87)	201	0	1,634
S3-a	98 (96)	183	0	1,634	83 (81)	197	0	1,634
S3-b	123 (72)	157	0	1,634	102 (60)	178	0	1,634
S4-a	---	---	---	---	87 (64)	193	0	1,634
S4-b	---	---	---	---	104 (76)	176	0	1,634

Note: Scenarios and cases are as defined in the text; values in parenthesis indicates % demand met

Since all the scenarios are run considering yield loss due to water stress for the crops grown in irrigation season, insight into the change in crop yield would be intriguing for the irrigation planner. The main crop in the dry season is the *Boro* rice and it shares the largest amount (around 70% as mentioned in Table 5.9) of the irrigation water supplied. Hence, only the change of *Boro* rice yield is analyzed as the representative crop and shown in Figure 8.3.

The potential yield of *Boro* rice considered in this study is 4.5 t/ha (as mentioned in Chapter 5) however, for any scenarios and cases this yield was not achieved. The most affected scenario is the dry year scenario with consideration of EF (S1-a, Case-II), where the yield is reduced to as low as 23% of the potential yield. It is due to very less flow is allowed for diversion to TIP in dry year. In baseline or existing scenario, irrigation demand is not fully satisfied from the river water and the yield reduced to 90 and 77% respectively for the case of EF not considered and considered. Once again expansion of irrigation area might not be a good decision when the *Boro* yield is considered. 81% of potential yield can be achieved when irrigated area is increased by 25% (Scenario S3-b, Case-I). Ensuring lower EF level (S4-b, Case-II) than the baseline scenario (S0, Case-II) results higher yield (83% rather than 77%) than baseline case due to allowance of more flow to divert to TIP. Overall, increased inflow, improvement of irrigation efficiency and less amount of EF provisioning affect positively to crop yield as it is observed for *Boro* rice from Figure 8.3.

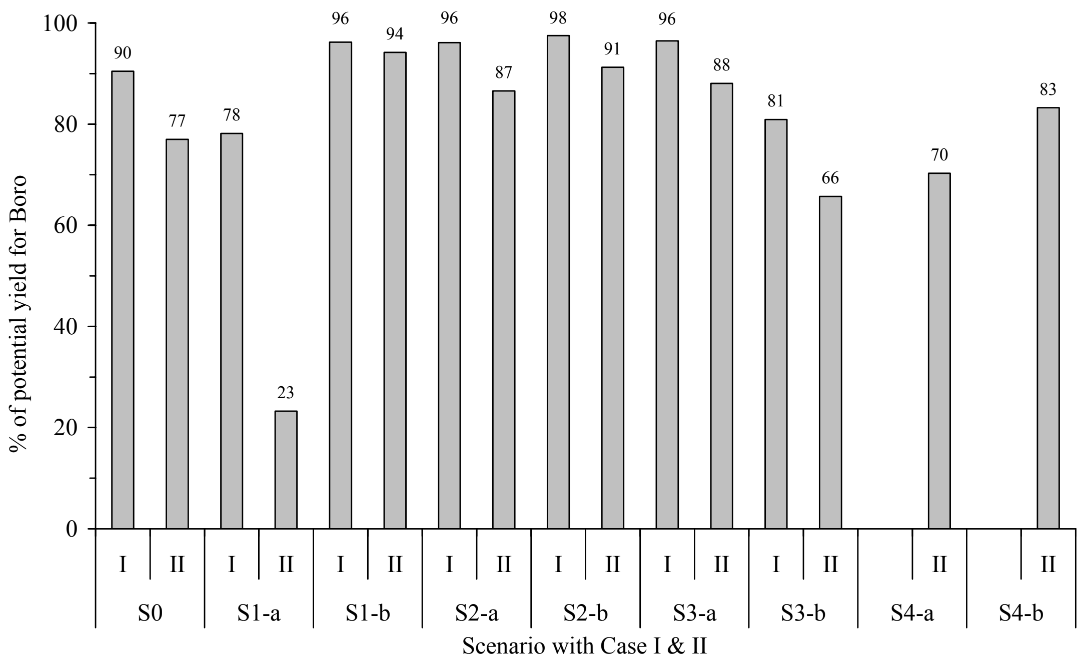


Figure 8.3 Change in *Boro* rice yield in different scenarios analyzed

Note: Scenarios and cases are as explained in the text

Offstream and instream benefits are estimated for each scenario and case, which are presented in Table 8.6. Higher benefit can only be achieved when more water is available either outside of the model boundary (higher inflow) or within the model boundary (by conserving water). Increase in flow level simultaneously increases both off- and in-stream benefits for both Cases of I and II. Same results come when water becomes higher due to increase in irrigation efficiency. Improving irrigation efficiency to 0.6 results the highest irrigation benefit and in this case the irrigation benefit (US$ 49.560 million) reaches almost to the maximum (US$ 49.587 million). Dry year scenario in Case-I results US$ 34.260 and 0.454 million for the off- and in-stream uses respectively, which are the lowest level of benefits from any scenario analyzed.

Table 8.6 Off- and in-stream water use benefits (in 10^6 US$) for the scenarios analyzed

Scenario	**Offstream benefit**		**Instream benefit**	
	Case-I	**Case-II**	**Case-I**	**Case-II**
S0	43.242	33.893	0.588	0.690
S1-a	34.260	8.884	0.454	0.651
S1-b	48.537	46.493	0.655	0.697
S2-a	48.361	40.791	0.612	0.691
S2-b	49.560	44.676	0.644	0.694
S3-a	35.331	28.778	0.624	0.692
S3-b	45.575	35.027	0.587	0.691
S4-a	---	30.660	---	0.724
S4-b	---	38.073	---	0.655

Note: Scenarios and cases are as defined in the text

With respect to the off- and in-stream benefits obtained from Scenario S0, Case-I (i.e. existing condition) the relative off- and in-stream benefits obtained in other scenarios analyzed (Case-I) are compared and presented in Figure 8.4. The increase in flow level always results higher benefit as evident from Figure 8.4. However, without consideration of EF at the downstream, TIP area can still be increased and it might result a higher irrigation benefit. It is due to the fact that in the month of November and April, all the available flow is not being used for irrigation since the demand is less at those months. It is evident from Figure 8.4 that the proportion of instream water use benefit reduction is higher than offstream benefit reduction when flow is reduced. In dry year scenario, the offstream benefit reduction is 17% whereas instream benefit reduction is 23%. Improvement of irrigation efficiency results higher benefit both from offstream and instream sectors. Improvement of irrigation efficiency up to 50% (baseline 40%) results eight and four percent benefit increase from off- and in-stream sector respectively.

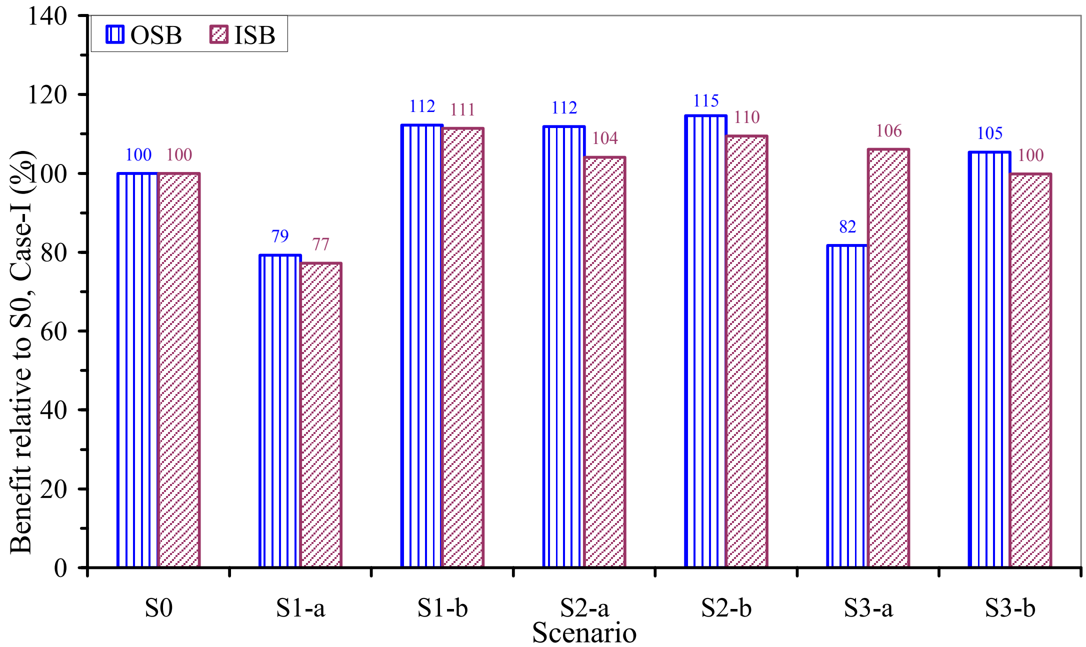


Figure 8.4 Benefits for offstream (OSB) and instream uses (ISB) in different scenarios analyzed for Case-I relative to Scenario S0, Case-I

Note: Scenarios are as explained in the text

Figure 8.5 presents the relative benefit from off- and in-stream sector as obtained from different scenario analyzed to the off- and in-stream benefits obtained from Scenario S0, Case-I (i.e. existing condition). As discussed in Chapter 4 that TIP was planned to be developed in phases and currently Phase-I is developed and Phase-II is under consideration of development. However, if EF is considered, expansion of TIP area might not be possible as it is shown in Figure 8.5, Scenario S3-b. Dry year scenario analysis (S1-a) indicates that current flow level is at margin to irrigation and EF demands. Currently instream flow benefits are mainly due to local flow from the area in between barrage to Kaunia. Nevertheless, if a small amount of flow is allowed for instream uses at the barrage point, it can generate a higher (11%) instream benefit and this becomes clear from Figure 8.5, Scenario S4-b. The figure shows that even if the Teesta water management authorities are not willing to provide baseline EF (i.e. RVA target based on +/- 1 SD), scope is available to accrue more instream benefit by ensuring less EF (as shown in Figure 8.5 Scenario 4-b).

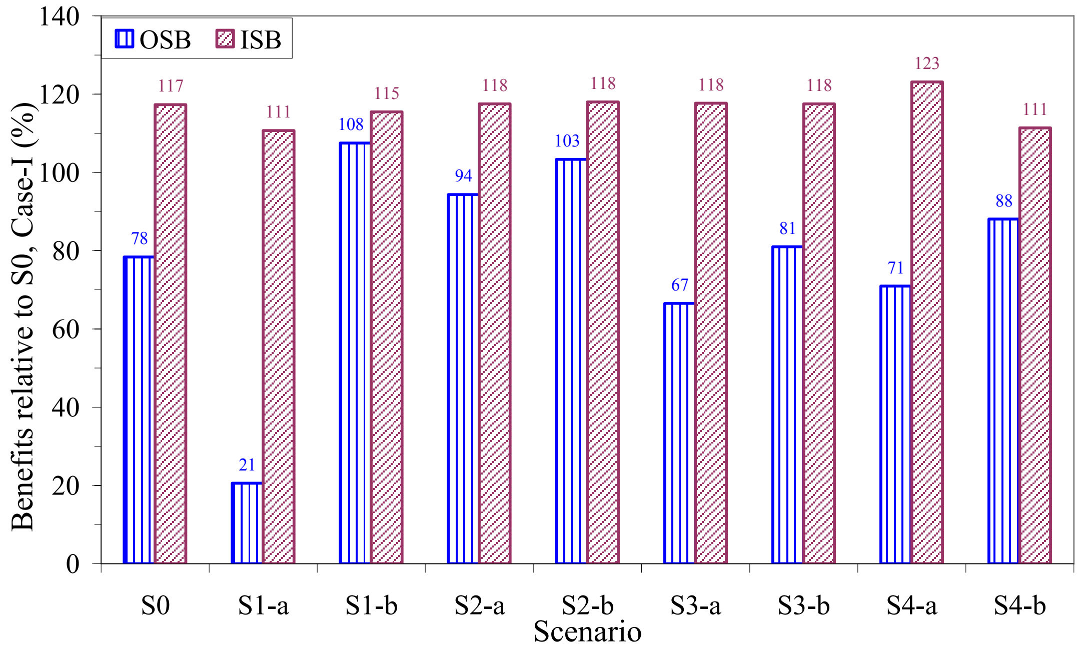


Figure 8.5 Benefits for offstream (OSB) and instream uses (ISB) in different scenarios analyzed for Case-II relative to Scenario S0, Case-I

Note: Scenarios are as explained in the text

Since framers in general irrigate their field by groundwater when river flow falls short, irrigation benefit from such case for all the scenarios are also analyzed. Farmers may choose to reduce the crop coverage to fulfill 100% irrigation demand with less available flow. Irrigation water use benefits for this case are also calculated and presented in Table 8.7. Previously calculated benefit for all the scenarios considered based on yield loss due to water stress are also given in Table 8.7 in the last column to compare the benefits obtained from other cases. Use of groundwater as supplement to surface water based irrigation at TIP results the highest benefit level, whereas reduction in crop coverage to get 100% irrigation water from the river results almost the same level of benefit as obtained from the yield loss case (also shown in Figure 5.3).

Analyses show that groundwater use requirement ranges from 7 to 741 mm for the entire irrigation season. In a study, Wahid et al. (2007) showed that the groundwater safe abstraction potential in TIP is in the range of 296 to 860 mm, which indicates in some area farmers might not be able to meet their irrigation demand by ground water pumping. However, their practices of groundwater use is worthy in economic sense as well as within the limit of safe abstraction to some area. For example in dry year scenario, highest amount of groundwater withdrawal is required (311 and 703 mm respectively for Cases I & II), which is still within the safe limit of groundwater abstraction, however it can hold the irrigation benefit to better level than reduction in crop coverage or yield loss due to water stress case. Improvement in irrigation efficiency results less amount of groundwater to be withdrawn such as only 54 and 7 mm (for Case-I) is required for 0.5 and 0.6 irrigation efficiency respectively. Expansion of irrigation land is also possible using groundwater supplemented irrigation and in that case 503 and 741 mm of groundwater are required for case I and II respectively. This amount of groundwater withdrawal is still within the range of safe abstraction limit for some places and beyond the limit for some place within the

TIP area. Proper planning is required to adopt conjunctive use of groundwater and surface water irrigation in TIP for a sustainable irrigation and crop yield.

Table 8.7 Offstream water use benefits (10^6 US$) for cases of groundwater supplemental irrigation, reduction in crop coverage to meet full irrigation demand and crop yield loss due to water stress at various scenarios

Scenario	Case	GW req (mm)	Economic benefit with		
			GW supplement to meet full irrigation requirement	Reduced crop coverage to meet full irrigation supply from river water	Crop yield loss due to water stress
S0	I	145	48.210	42.970	43.242
	II	317	46.582	35.040	33.893
S1-a	I	311	46.642	35.334	34.260
	II	703	42.941	17.299	8.884
S1-b	I	36	49.232	47.951	48.537
	II	79	48.827	45.977	46.493
S2-a	I	54	49.068	47.815	48.361
	II	286	46.879	40.213	40.791
S2-b	I	7	49.512	49.312	49.560
	II	156	48.109	43.465	44.676
S3-a	I	63	36.745	35.951	35.331
	II	330	34.852	30.691	28.778
S3-b	I	503	56.047	45.485	45.575
	II	741	53.241	37.689	35.027
S4-a	II	373	46.061	32.500	30.660
S4-b	II	243	47.286	38.468	38.073

Note: Scenarios are as explained in the text; Case-I: minimum environmental flow demand at downstream is not considered; Case-II: minimum environmental flow demand at downstream is considered

8.3.3 Environmental flow – a societal choice

Environmental flows can be regarded as not exactly empirically determined figures, but they are more value judgments depending on the aim of river management. Specific physical situation and the expected state of the ecosystem should control the EF decision making. Without limiting the economic growth, keeping nature happy by protecting environment is the main challenge along this line and this can be done within the context of wider assessment framework that contributes to river basin planning and management. Bearing in mind such issues, three different levels of EF namely, low, medium and high EF are considered in optimal water allocation in Teesta. In low EF level, RVA target is set at +/-1.5 SD, whereas in medium and high EF level RVA target is set at +/-1 SD and +/-0.5 SD respectively. Detailed results on EF requirements for the three levels of EF are presented in Table 7.6.

Table 8.8 presents the sectoral benefit and their percentage with respect to total benefit as estimated in S0 Case-I for different level of EF provisioning. At low EF level (i.e. RVA target set at +/- 1.5 SD), the dry season flow is in between 116 – 120 m^3/s, which is in between ‘good’ and ‘fair’ status as defined by Tennant. With this level of EF, optimization model gives the total benefit of US$ 38.728 million (US$ 38.073 million from offstream and US$ 0.655 million from instream). Increasing EF level at medium (i.e. RVA target set at +/-1.0 SD) level needs 134 – 150 m^3/s of flow, which is again in the same status given by Tennant. Provisioning this level of EF results reduction in benefit level and overall benefit goes down to US$ 34.583 million. However, instream water use benefits increase here from the previous case by US$ 0.035 million. Further increase in EF level (i.e. RVA target set at +/- 0.5 SD) prescribes a flow of 150 – 181 m^3/s, which is about to reach the ‘good’ status based on Tennant method. In this EF level overall benefit goes down to US$ 31.384 million which is US$ 3.199 million lower than the benefit achieved from EF-medium level. Instream water use benefit increases by US$ 0.034 million from the previous case.

Table 8.8 Sectoral benefit and their changes at different level of EF provisioning for Teesta

EF level	**Sectoral benefit (10^6 US$)**			**Benefit as % total benefit of S0 Case-I**		
	Offstream	**Instream**	**Total**	**Offstream**	**Instream**	**Total**
Low	38.073	0.655	38.728	86.87	1.49	88.36
Medium	33.893	0.690	34.583	77.33	1.57	78.90
High	30.660	0.724	31.384	69.95	1.65	71.60

Comparison of the benefits achieved from both in- and off-stream uses for all three cases are depicted in Figure 8.6. From the Figure 8.6 and Table 8.8 above, it is evident that increase in EF level results overall decrease in benefit level. However, percentage change is offstream benefit is higher than instream benefit, which again reflects the higher marginal benefit of offstream sector than instream sector.

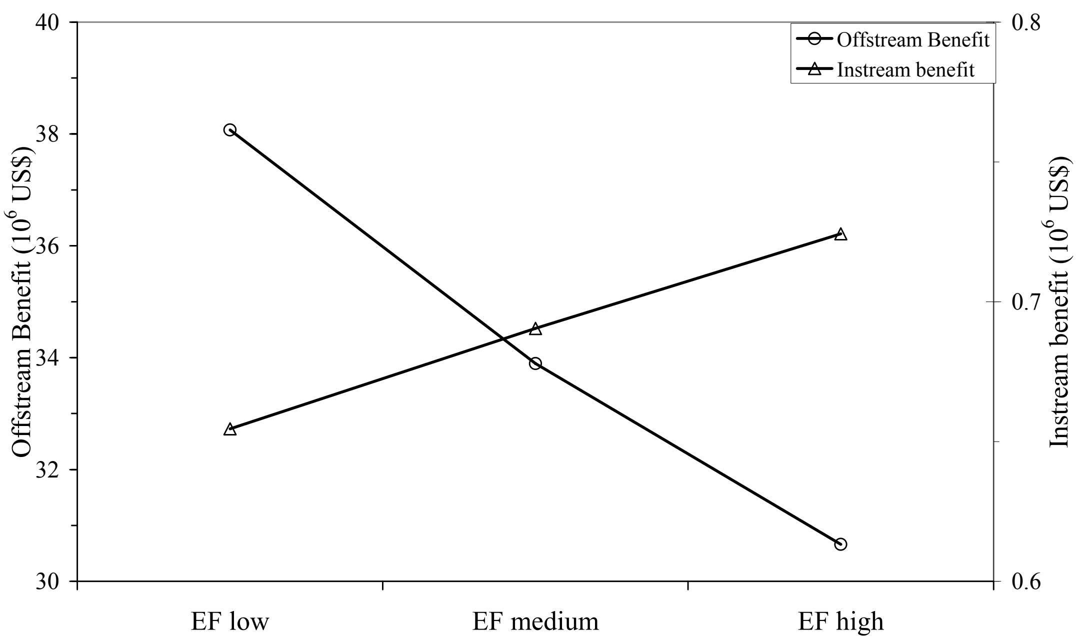


Figure 8.6 Change in off- and in-stream benefits due to change in EF level

Note: EF low = RVA target set at +/-1.5 SD, EF medium = RVA target set at +/-1.0 SD; EF high = RVA target set at +/-0.5 SD

8.3.4 Tradeoff analysis

The flow in river is crucially important for the agricultural production and subsequently for poverty alleviation and reduction of hunger gap. However, river flow also maintain the ecosystem, keeps the river clean by flushing the waste, replenish nutrients in the soil, support fisheries that feed the society and provide transportation which is the cheapest and the only mode of transportation in the rural site of Teesta river. Achieving benefits from both sides ask for tradeoff to certain extent. Without and with consideration of monthly environmental water demands at the downstream, total benefits for different scenarios are analyzed and the tradeoff for maintaining EF is found out.

Benefits from several scenarios are compared with the benefit garnered from Scenario-0 case I (i.e. baseline without considering EF). Figure 8.7 depicts the tradeoff picture between economic efficiency and environmental protection for the Teesta study site. Severe situation occurs in dry year scenario where reduction in benefit is 57% if environmental protection is ensured through providing EF. In baseline scenario, society has to compromise about 20% reduction in overall benefit if EF is ensured. However, the benefit reduction level can be improved to 12% if a low level of EF is maintained (S4-b). Improvement of irrigation efficiency to 0.5 (baseline 0.4) results 12% (S2-a) increase in benefit from baseline if EF is not provided, however, reduction in overall benefit after having EF is only 5% (S2-a) from baseline scenario. If irrigation efficiency can go up to 0.6 overall benefits would be increased by 4% (S2-b) from the baseline scenario even after ensuring EF.

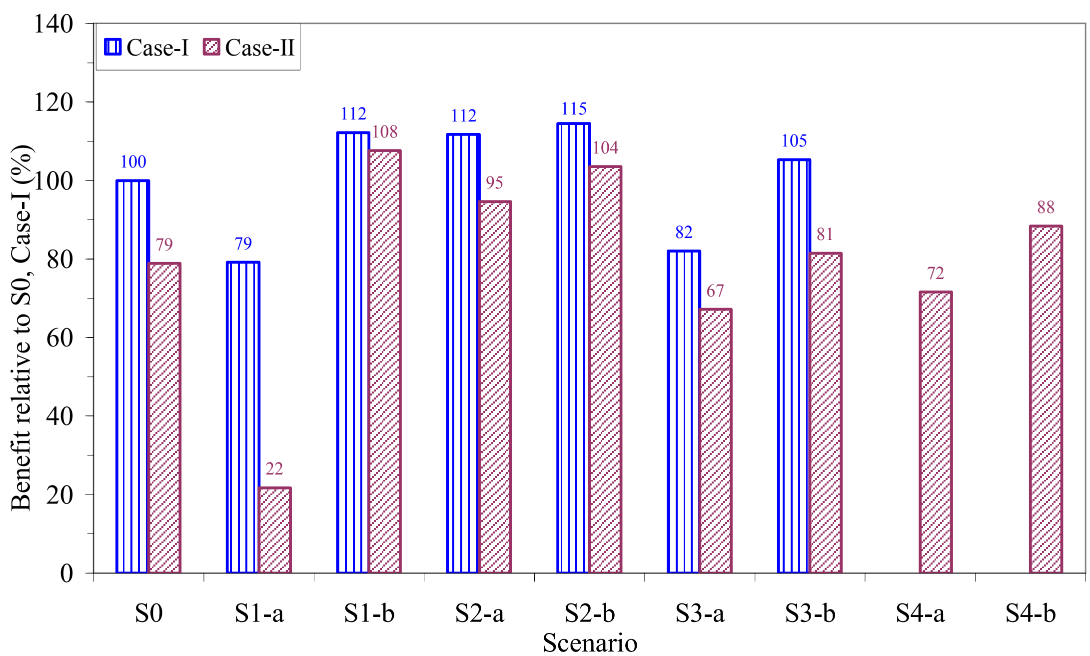


Figure 8.7 Tradeoff between economic efficiency and environmental protection based on total benefit from Scenario S0, Case-I for the Teesta study site

Note: Scenarios are as explained in the text

Overall, maintaining environmental protection reduces the total benefit in any scenario analyzed. This is due to high offstream benefit and low instream benefit. However, increase in basin benefit without decrease in either off- or in-stream sector can only be possible by having more inflow outside of the model boundary or by improving irrigation efficiency and conserving more water within the model boundary.

8.4 Concluding remarks

The outcomes of the analyses clearly show the sectoral benefits and tradeoff scenario while allocating water to in- and off-stream water users. Decision makers in many developing countries often overlook the required balance between allocating water for out of stream direct uses namely: domestic supply, agriculture, industry etc. and allocating water for instream uses. However, the optimal water allocation and related benefits as estimated in this chapter will help water management authorities in realizing in particular the benefit from instream water direct uses, which will eventually promote EF provisioning. It has been pointed out that the current operation does not satisfy EF demands at the downstream part of Teesta; hence, ensuring EF is recommended at least to the lower level as considered in the study. Since the instream water users are mainly the poor and their livelihood is entirely based on the flow in the river, ensuring a certain flow level will eventually help in socio-economic development of the region, which will ultimately lead to a pro-poor water management.

Das Gupta (2008) mentioned that since withdrawals of water increase, many river basins will face the challenge of maintaining the critical levels of environmental flows in near future. The process is unlikely to be reversed until agriculture uses water more efficiently and environmental flow allocation is integrated into river basin management plan. Analyses and results in this chapter also depicts that improvement in irrigation efficiency is vital to sustain economic benefit and river health protection simultaneously.

Finally, the analyzed results provide a reasonable starting point for reconciling the competing needs of the instream and offstream water uses and will act as a basis for informed policy decision and adopting pro-poor and environmentally sound water management particularly in Bangladesh context.

PART-III

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9 KONTO RIVER BASIN: STUDY SITE IN INDONESIA

9.1 The Konto River Basin, Indonesia

The Konto River Basin in the Java Island, Indonesia is selected as the other study site for this research. The river is a tributary of the Brantas River. The Brantas Basin, approximately 11,800 km^2 in areal extent, lies entirely within the province of East Java, Indonesia, between $110^0$30' and $112^0$55' East Longitude and $7^0$01' and $8^0$15' South Latitude. The length of Brantas is about 320 km and has its headwaters in the Arjuno volcanic massif, a major topographic feature dominating the southeast -central portion of the basin. It courses clockwise around the massif, south through the Malang Plateau (elevation 400 M), then west through the major dam and reservoir complex consisting of Sengguruh, Lahor, Sutami, Wlingi and Lodoyo, respectively. Figure 9.1 presents the Konto river basin within the Brantas river system and Figure 9.2 presents the Brantas river system with its main reservoirs mentioning the year of commissioning of the reservoirs. At the confluence with the Ngrowo River in the Southwestern portion of the basin, the Brantas turns north through the agriculturally productive plains region and finally east through the delta, also an important paddy growing area, where it discharges into the Madura Strait. Primary tributaries above the delta include the Lesti (Southeast), Ngrowo (Southwest), Konto (Central), Widas (Northwest) and Surabaya (Northeast) Rivers (Rodgers and Zaafrano, 2002). Table 9.1 presents the sub-basin areas of the Brantas river system

Table 9.1 Sub-basins with their areas of the Brantas river system

Brantas river Sub-basin	Catchment area (km^2)
Lesti	625
Konto	687
Widas	1,539
Brantas	6,719
Ngrowo	1,600
Surabaya	631
Total Brantas basin	11,800

Source: Subijanto et al. (2009)

The upper part of Konto catchment is located about 25 km northwest of the city of Malang in East Java and constitutes one of the important headwater areas of the Brantas River system. The eastern part of the catchment (Pujon area) consists of an inter-volcanic plain surrounded by hilly (950–1,300 m a.s.l.) and mountainous (up to 2,889 m) landforms. The western part (Ngantang area) consists of three adjoining gently sloping inter-volcanic plains at an elevation of 620–800 m a.s.l. bordered by the foot-slopes of Mounts Kelud (1,731 m) and Kawi (2,631 m) on the one hand and by the western spurs of the Anjasmoro mountains on the other. The two plateaux are connected by the narrow gorge of the Konto River cutting through the respective foothills of Mt Kawi and the Anjasmoro range (Rijsdijk et al., 2007). Konto then meets with Lake Selorejo. The Konto at the downstream of Selorejo flows towards north-west and finally drains into the Brantas River.

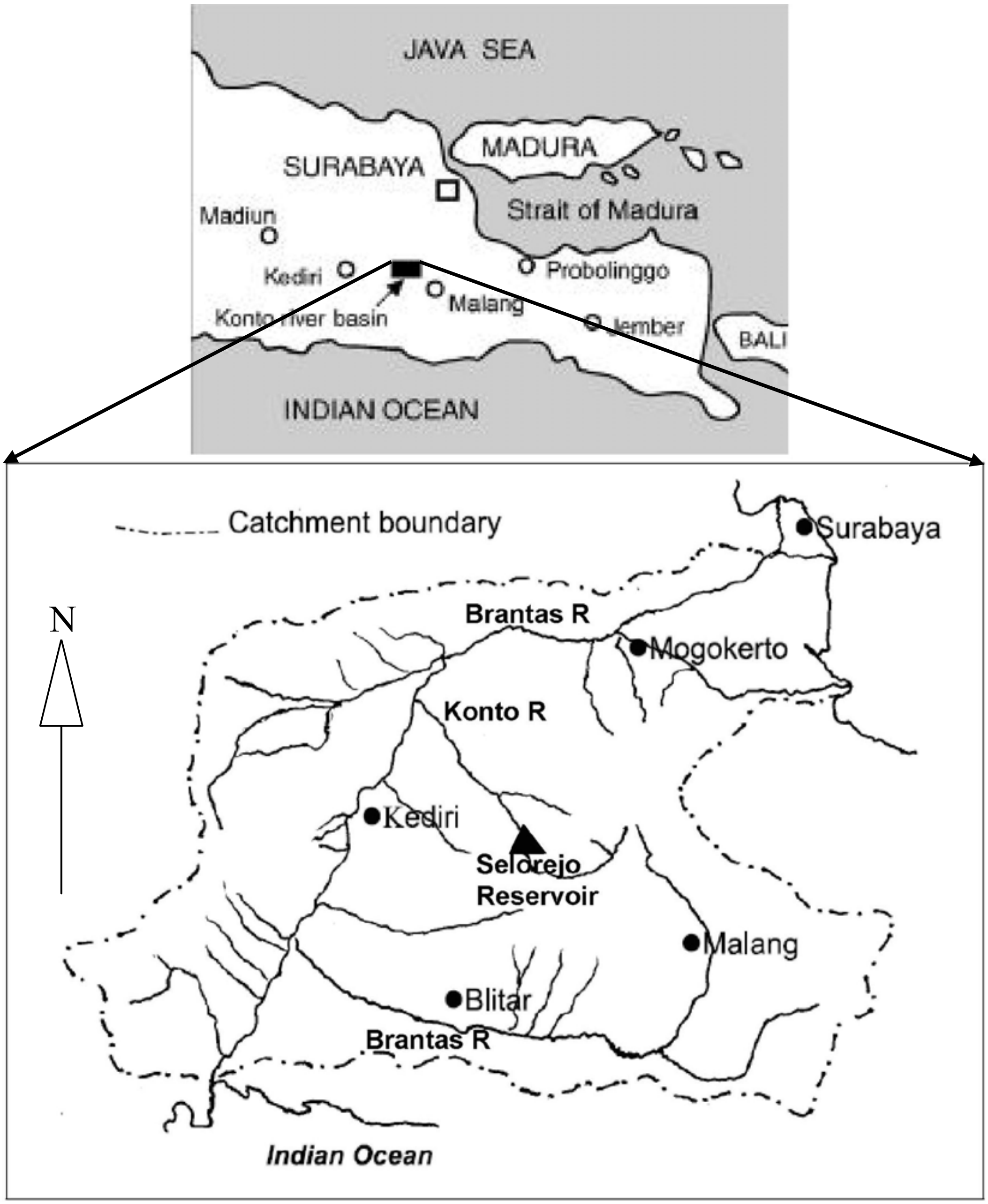

Figure 9.1 The Konto River in the Brantas river system

The total basin area of the Konto is 687 km^2 which can be divided into two parts upper (above Selorejo reservoir) and lower (downstream of Selorejo reservoir). Catchment area for the upper part is about 236 km^2 that comprises Konto River 148 km^2, Kwayangan River 12.5 km^2, Pinjal River 44.3 km^2 and Selorejo reservoir 31.3 km^2. Lower part of the Konto basin has an area of 451 km^2. Three small tributaries are found meeting the Konto in this lower part, namely: Sambong (catchment area 3.13 km^2), Nogo (catchment area 1.35 km^2) and Nambaan (catchment area 3.69 km^2) (Solihah, 2011). Average annual rainfall in the basin is about 2,700 mm whereas annual average evaporation is about 1,470 mm. The annual average temperature is 23.5^{0}C, with maximum monthly temperature of 24.5^{0}C in January, and a minimum temperature of 22.7^{0}C in July. Annual average relative humidity is 79.9%, with a minimum humidity of 75% in January, and maximum of 83% in September (Solihah, 2011). Figure 9.3 shows the schematic of the lower part of the Konto River (the study site) including the water uses.

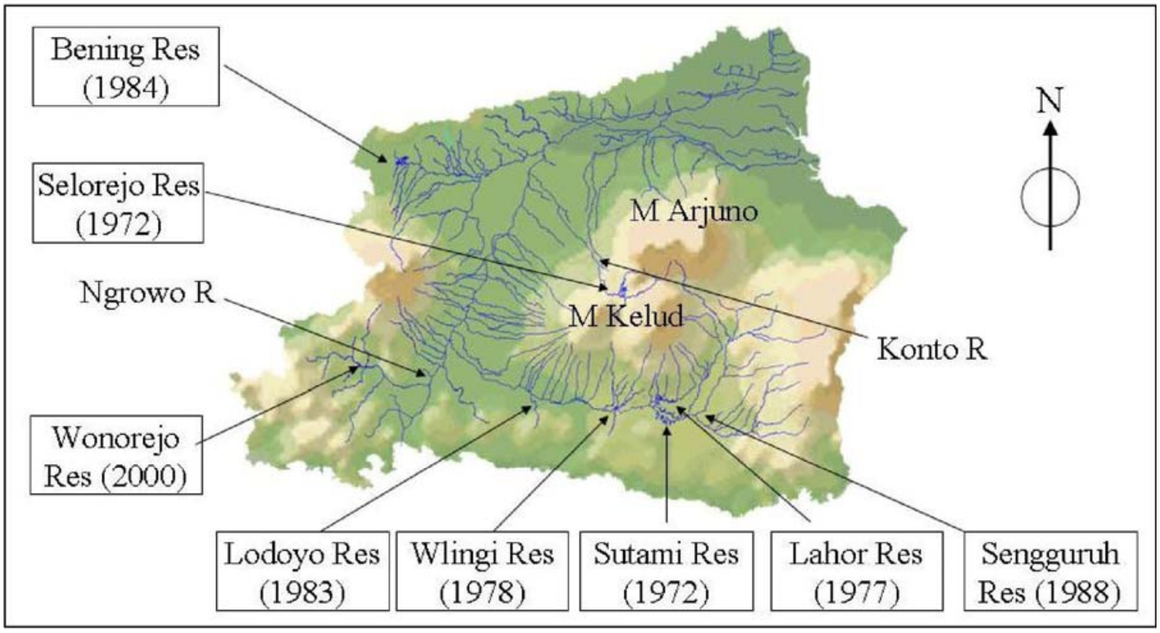

Figure 9.2 The Brantas river system with main reservoirs
Source: Subijanto et al. (2009)

Owing to the location of the entire Brantas basin in the Inter-tropical Convergence Zone, the semiannual reversal of prevailing winds results in distinct wet (November -April) and dry (May-October) seasons in the region; on average the wet season encounters around 25 rainy days per month, compared to seven or fewer during the dry season (Rodgers and Zaafrano, 2002). Roughly 80% of the rainfall occurs in the wet season. The plains and delta which consist of alluvial soils (silt, clay loams) are well suited to paddy cultivation.

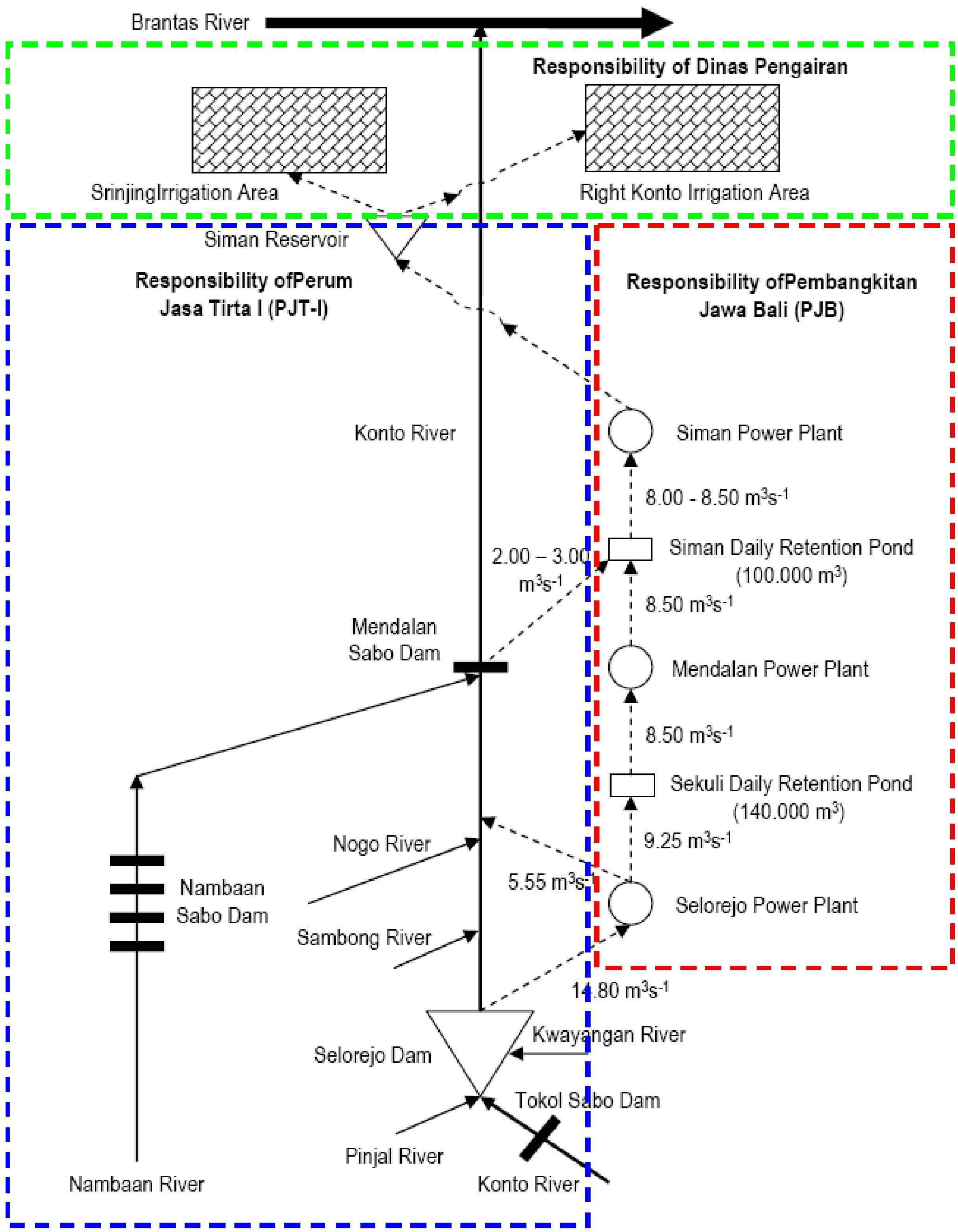

Figure 9.3 Schematic of the Konto study site

Note: Discharge values mentioned in the figure are the capacities of tunnel/pipes

9.2 Water resources development in the basin

Selorejo dam and reservoir is the main important infrastructure in the Konto river basin. The reservoir is situated at the upper part of Konto having a catchment area of 236 km^2. In addition to Konto inflow, the reservoir is fed by Pinjal and Kwayangan rivers. Commissioned in 1970, the reservoir is equipped with a hydropower plants named Selorejo hydropower plant. The reservoir is also used for recreation and fishery purposes. The capacity of the reservoir is about 40x10^6 m^3 with a water surface area of 4 km^2 at the normal maximum capacity. The Selorejo hydropower started operating since 1972 having an installed capacity of 4.5 MW and the design discharge of 14.8 m^3/s. The release from Selorejo hydropower plant was redirected to the Konto until 2003 before the construction of two hydropower plants.

The topography of the region resonates well in terms of getting considerable heads in building two other hydropower plants, namely: Mendalan and Siman. These two plants are run-off-river type power plant and came into operation in 2003. The tail water elevation of the Selorejo power plant is 582.00 m a.m.s.l. Part of the release from Selorejo plant is taken through a 3.25 km long tunnel to Sekuli daily retention pond which stabilizes the discharge from Selorejo and supplies water to Mendalan hydropower plant having an installed capacity of 7.0 MW and design discharge of 8.5 m^3/s. The tunnel capacity that feeds Sekuli retention pond is 9.25 m^3/s. A 5.55 m^3/s capacity pipe sends back the extra discharge from Selorejo to Konto. Water elevation of the Sekuli pondage is 573.17 m a.m.s.l. and the tail-water elevation of Mendalan power plant is 422.90 m a.m.s.l. (PJT-I, 2007).

The release from Mendalan power plant goes through a 3.2 km long tunnel and feeds Siman Retention pond where Siman Hydropower plant is installed with the capacity of 9.0 MW and with design discharge of 8.5 m^3/s. The effective head of Siman hydropower plant is 106.4 m. At the point of confluence of Mendalan River with the Konto, provision of 2 – 3 m^3/s flow diversion to Siman pond is installed to stabilize the power production from Siman plant (Solihah, 2011). The water used in Siman power plant goes to Siman reservoir from where the Konto irrigation area (including Srinjing and Right Konto irrigation area as shown in Figure 9.3) projects gets supply of irrigation water. The key water resources development information is documented in Table 9.2.

Table 9.2 Key water resources development structures with their main features in Konto river basin

Water resources development structure	**Year installed**	**Main feature**
Selorejo dam and reservoir	1970	Capacity: $40x10^6$ m^3 Equipped with hydropower, reservoir is also used for fisheries and recreation
Selorejo hydro-power plant	1972	Installed capacity: 4.5 MW Equipped with Selorejo dam Max head: 40.00 m
Mendalan hydropower plant	2003	Installed capacity: 7.0 MW Runoff river type Effective head: 150.27 m
Siman hydropower plant	2003	Installed capacity: 9.0 MW Runoff river type Effective head: 106.40 m

9.3 Water uses in the Konto River Basin

The main water uses in the Konto river basin are:

Hydropower – the foremost water use in the basin is power generation and it starts from the Selorejo reservoir. A series of hydropower plants are operating beside the river Konto. Outflow from one power plant is fed into another plant. Since the water is actually not consumed for hydropower production, the same water is used three times to produce power and then the water is finally used for irrigation.

Irrigation – following the water used in three hydropower plants installed in series, the water goes to irrigation project. There are two parts of the project located at the two sides of Konto, namely: left- and right-Konto irrigation area with a total area of 30,461 ha. The main crop in the project area is paddy (lowland rice). Other crops include coffee, cassava, maize, peanuts and soybeans. The irrigated dry season crop including maize, soybeans and peanuts, are collectively known as *Palawija*. Three seasons are predominant in agricultural practices; namely: wet season (November – February), first dry season (March – June) and second dry season (July – October).

Reservoir fisheries and recreation – the water in Selorejo reservoir is also used for fishery and recreational purposes. Annual average fish production from the reservoir is about 113.5 tonne (DoF, Malang, 2010) and annual average recreationists to the reservoir are about 173,212 person based on last eight years (2001 – 2008) information.

In addition to the use of the water for hydropower, irrigation, fishery and recreation the flow in the Konto is also used for municipal and industrial purposes. Drinking water supply from the Konto is about 0.04 m^3/s whereas for industrial is 0.66 m^3/s, which makes a total M&I supply of 0.70 m^3/s. Besides all these uses, flow in the Konto is important for maintaining proper functioning of the riverine system including few subsistence uses (mainly subsistence irrigation and fishery) by the riparian population.

9.4 Socio-economic condition

Information referring to socio-economic condition of Konto Basin is very rare; however, overall socio-economic condition of the Brantas basin is available in few literature. Population density in the Brantas basin is 1,248.7 inhabitants/km^2, which is quite dense compared to the Java island population density of 918.9 inhabitants/km^2 and East Java population density of 724.3 inhabitants/km^2. Total population in the basin is close to 15.2 million people according to 2000 census data, which counts for about 42% of East Java population. Renewable water in Java is only 1,540 m^3/person/year, compared to the Indonesian average of 15,600 m^3/person/year due to high population density in the Java (Rodgers and Hellegers, 2005).

Besides the population, the Regional Gross Domestic Product (RGDP) for the basin is quite high, valuing approximately US$ 10.97 billion (IDR 98.8 trillion) in 2000 (ADB/IFPRI, 2003) that is 58% of the RGDP for East Java (Sunaryo, 2001). This prosperity is supported among others by the water availability related to the infrastructures in the basin. Agriculture is the mainstay in economic activity of this region. Rice is the principal crop grown all over the whole year. In the year 2004, rice production in Brantas basin was 2.99 million tonne whereas the production for the entire East Java was 9.22 million tonne (Subijanto et al., 2009).

The Brantas basin is a very well developed river basin in Indonesia in terms of water sector investment and water resource utilization, next to the Citarum River basin in West Java. It is also the best-managed river basin in Indonesia where a holistic approach to basin water resource management has been adopted. Investment in flood control and water infrastructure has helped development of an industrial belt at the downstream Surabaya-Gresik area and has increased agricultural production of the basin. In last three decades, rice production has doubled while non-rice crop production has seen a ten-fold increase. Hydropower generation capacity has increased from 4.5 MW in 1972 to 263 MW (Subijanto et al., 2009). All such developments contribute positively in socio-economic development to a large extent in the basin. Brantas basin covers nine regencies and five municipalities. Starting at the upper regions of the river they are Malang, Blitar, Tulungagung, Kediri, Nganjuk, Jombang, Mojokerto, Sidoarjo, and Surabaya City, including portions of Pasuruan and Gresik (Subijanto et al., 2009).

9.5 Water management of the Konto

The water resources in the Brantas basin including Konto are principally managed and maintained by *Perum (Perusahan Umum) Jasa Tirta*-I Public Corporation (PJT-I). PJT-I established in 1990, based on Government Regulation No. 5/1990 is charged with managing the water resources in 40 of the more important benefit producing rivers (including the Brantas River) in Java. The Corporation is responsible to protect the river morphology, for operating, maintaining, and managing the major infrastructure in these rivers and managing flood.

The corporation, however, has no policy power in areas such as basin planning, basin infrastructure development and investment, off-stream water quality improvement, tariff fixing etc. In these areas where it is not permitted to make policy decisions, PJT-I works through the administrative and consultative channel to influence decisions. As an organization PJT-I has been very effective in most aspects of the WRM decision-making, coordination, improving resource base, and working with other basin agencies and stakeholders by adopting a proactive management style and having a good working relationship with both formal and informal institutions.

The activities of the corporation cover (i) bulk water supply for irrigation systems, (ii) raw water for domestic and industrial purposes, (iii) water supply for hydropower plants, (iv) land rent and limited sand mining, (v) tourism in its working area, and (vi) construction and consulting services (Subijanto et al., 2009). The main functions of PJT-I are (i) water quantity management, (ii) water quality management, (iii) flood control management, (iv) river environment management, (v) watershed management, (vi) water resources infrastructure management, and (viii) research and development. In carrying out these activities, the corporation coordinates with stakeholders such as the State Electricity Corporation, municipal water supply corporations, private and public sector industries, NGOs, and experts.

PJT-I is supervised by a supervisory board composed of central and provincial government representatives and is managed by a board of directors headed by a president director. Being a national corporation, the authority to oversee the management and functioning of

PJT-I lies with the center through the Ministry of Public Works, with the Ministry of State-owned Corporation (MoSC) exercising a fiscal oversight role.

The corporation is not responsible for irrigation system management but provides bulk water. Irrigation management and decision making is primarily a provincial subject matter. Irrigation services are managed by *Dinas Pengairan*, which works closely with East Java provincial water office. In cases where water supply is made from the irrigation system for non-irrigation functions (water supply to industry), the corporation coordinates with the concerned irrigation agency. Thus, much of the management decisions are based on a consultative process through a proactive approach. The corporation is authorized to make most of the technical policy decisions and some policy decisions related to WRM, such as release of reservoir water for flushing, changes in water allocation during times of shortage, reservoir operation, awareness campaign etc.

The hydro-electric power plants are owned and operated by the state electricity company (PLN) while PJT-I operates the dams and provides the bulk water for power generation. *Pembangkitan Jawa Bali* (PJB), a subsidiary company of PLN is responsible for managing power production including hydropower plants in East Java and Bali Island. Established in 1995, PJB is intended to decentralization program, enhance efficiency and increase quality service delivery to the public. PJB pays PJT-I a tariff for water supply, which is reviewed each year and is approved by the Ministry of Public Works, based on the recommendation of the Ministry of Finance (MOF).

In the Brantas basin, raw water for domestic purposes is provided for fourteen regional water supply enterprises known as Perusahaan Daerah Air Minimum (PDAMs) that provide treated drinking water to urban areas. PDAM are managed as public corporations under the authority of the district government. The East Java Water Resources Office is the responsible agency (on behalf of provincial governor) for issuing licenses for raw water abstraction based on the recommendation of PJT-I while PJT-I is responsible for water allocation. The industrial water supply is regulated by licenses issued by the East Java Water Resources Office based on the recommendation of PJT-I.

9.6 Data and information collection

Several data and information related to hydrology, reservoir and its operation, hydropower, irrigation and agriculture, fishery and recreation are collected mainly from PJT-I and department of fisheries (DoF).

9.6.1 Hydrological data

9.6.1.1 Inflow to Selorejo reservoir

Mean monthly inflow to Selorejo reservoir was collected for past ten years (1999 - 2008) and presented in Table 9.3. The inflow is calculated based on measured water level in the reservoir. Even though the reservoir is operated since 1970, only ten years inflow data was made available from PJT-I for this research. Based on the collected inflow data (Table 9.3) average annual inflow to Selorejo reservoir is about 10 m^3/s. Months of February and March have the maximum flow whereas August and September have the lowest flow.

Table 9.3 Monthly average inflow (m^3/s) to Selorejo reservoir (1999 - 2008)

Year	**Jan**	**Feb**	**Mar**	**Apr**	**May**	**Jun**	**Jul**	**Aug**	**Sept**	**Oct**	**Nov**	**Dec**	**Annual Average**
1999	14.31	17.87	16.73	14.37	9.51	7.49	7.37	6.65	6.28	8.09	10.63	16.78	11.34
2000	16.26	18.82	16.59	16.58	13.57	10.75	8.38	7.56	7.48	7.79	9.63	8.26	11.81
2001	11.88	18.50	15.03	13.97	10.05	9.62	8.06	7.06	6.96	10.83	9.31	9.44	10.89
2002	13.19	26.97	15.45	12.96	10.43	8.25	7.50	6.75	6.32	5.96	8.10	10.48	11.03
2003	8.93	15.27	14.82	8.51	8.13	6.70	5.89	5.51	5.55	5.40	8.21	8.03	8.41
2004	9.66	15.82	17.91	11.35	9.94	7.27	6.62	5.54	6.79	6.16	8.85	13.78	9.97
2005	9.68	8.73	10.42	12.25	7.73	6.87	7.00	6.10	6.16	6.73	7.14	11.05	8.32
2006	14.35	14.09	13.15	12.79	12.00	8.29	6.36	5.74	5.42	6.37	6.96	9.47	9.58
2007	6.93	13.52	14.35	13.93	8.99	8.23	7.10	6.56	6.18	7.55	9.51	17.07	9.99
2008	13.70	19.00	21.25	15.69	12.68	9.73	8.42	8.13	8.02	8.62	9.81	10.94	12.17
Monthly Average	11.89	16.86	15.57	13.24	10.30	8.32	7.27	6.56	6.52	7.35	8.82	11.53	

Source: PJT-I database, 2010

9.6.1.2 Sambong, Nogo and Nambaan river flow

The three small tributaries, namely: Sambong, Nogo and Nambaan river meet with Konto before the Mendalan *Sabo** dam. However, there is no observed flow data for these rivers. As part of this research, the flows of these rivers are estimated using NRECA (Fritz, 1984) model. NRECA model calculates the monthly flow using meteorological data. On ungauged streams where stream flow measurements are not available, precipitation and potential evapotranspiration records can be used to calculate continuous flow. The calculation uses monthly precipitation and potential evapotranspiration data to calculate monthly streamflow based on following water balance equation:

Precipitation – actual evapotranspiration + storage = runoff

Following steps are involved in calculating monthly runoff:

- Assembling concurrent monthly rainfall and potential evapotranspiration data
- Estimating watershed characteristics of the basin
- Calculating monthly streamflows based on rainfall and evapotranspiration data (using a spreadsheet)

Three coefficients represent the watershed characteristics, namely: NOMINAL, PSUB and GWF. NOMINAL is an index to the soil moisture storage capacity in the watershed measured in mm; PSUB is the fraction of runoff that moves out of the watershed as baseflow or groundwater flow, which is dimensionless and GWF is an index to the rate of discharge from the groundwater storage to the stream, dimensionless. These watershed characteristics are estimated from limited field data based on historic streamflows. NOMINAL controls the runoff with an inverse relationship. GWF controls the low

* *Sabo* dam is a kind of silt arresting dam

streamflows between storms, whereas PSUB increases or decreases the volume of water moving on the subsurface flow paths. Having the watershed characteristics, monthly runoffs are calculated using a spreadsheet, detail calculations are based on Fritz, 1984 and carried out as part of this research by Triweko et al. (2010). Values of the watershed characteristics coefficients, NOMINAL, PSUB and GWF are considered as 643.6 mm, 0.80 and 0.10 respectively for all the three tributaries. The estimated monthly flow for Sambong, Nogo and Nambaan rivers for past ten years (1999 – 2008) are presented in Table 9.4. The annual average flow for the three river in combined is about 0.4 m^3/s whereas the maximum monthly flow is estimated 0.66 m^3/s in February and minimum flow is estimated to be 0.25 m^3/s for the months of September and October. Detail data on monthly flow for past ten years for individual rivers are reported in Table F.1 Appendix F.

Table 9.4 NRECA model estimated flow (m^3/s) for Sambong, Nogo and Nambaan rivers (1999 – 2008)

Year	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Annual Avg
1999	0.91	0.88	0.87	0.87	0.58	0.54	0.47	0.42	0.39	0.46	0.53	0.76	0.64
2000	0.77	0.99	0.79	0.73	0.59	0.51	0.45	0.40	0.37	0.33	0.45	0.30	0.56
2001	0.60	0.72	0.76	0.66	0.45	0.49	0.38	0.34	0.32	0.41	0.41	0.28	0.49
2002	0.59	1.14	0.64	0.52	0.43	0.40	0.35	0.31	0.29	0.25	0.24	0.27	0.45
2003	0.28	0.50	0.61	0.33	0.28	0.26	0.23	0.21	0.19	0.17	0.25	0.25	0.30
2004	0.30	0.59	0.69	0.35	0.31	0.29	0.25	0.23	0.21	0.18	0.19	0.25	0.32
2005	0.19	0.25	0.26	0.25	0.17	0.16	0.14	0.13	0.12	0.10	0.11	0.28	0.18
2006	0.42	0.48	0.42	0.27	0.38	0.25	0.22	0.20	0.19	0.16	0.15	0.24	0.28
2007	0.14	0.37	0.42	0.41	0.24	0.22	0.20	0.18	0.16	0.16	0.23	0.43	0.26
2008	0.47	0.71	0.90	0.51	0.43	0.39	0.34	0.30	0.28	0.26	0.30	0.35	0.44
Monthly Avg	0.47	0.66	0.64	0.49	0.39	0.35	0.30	0.27	0.25	0.25	0.28	0.34	0.39

9.6.1.3 Local flow for Konto downstream of Selorejo reservoir

Using NRECA model, the flow of the Konto River downstream of Selorejo that meets Brantas River is also estimated by Triweko et al. (2010) and compared with the observed flow. Sufficient data and information regarding the watershed characteristics coefficients were not available to estimate the local flow of Konto. Coefficient values similar to Sambong, Nogo and Nambaan are therefore used to estimate the local flow of Konto. Mean monthly flows of Konto that meets Brantas for past five years (2004 – 2008) were obtained from PJT-I (2010a) as observed data and reported in Table F.2 in Appendix F. Table F.3 (Appendix F) presents the NRECA model calculated flows for 2004 – 2008. Figure 9.4 shows the observed and NRECA model calculated Konto local flow. Difference in flow between observed and estimated (Figure 9.4) is considerable particularly in wet season. It is due to use of incorrect values of watershed characteristics coefficients, which has already been mentioned.

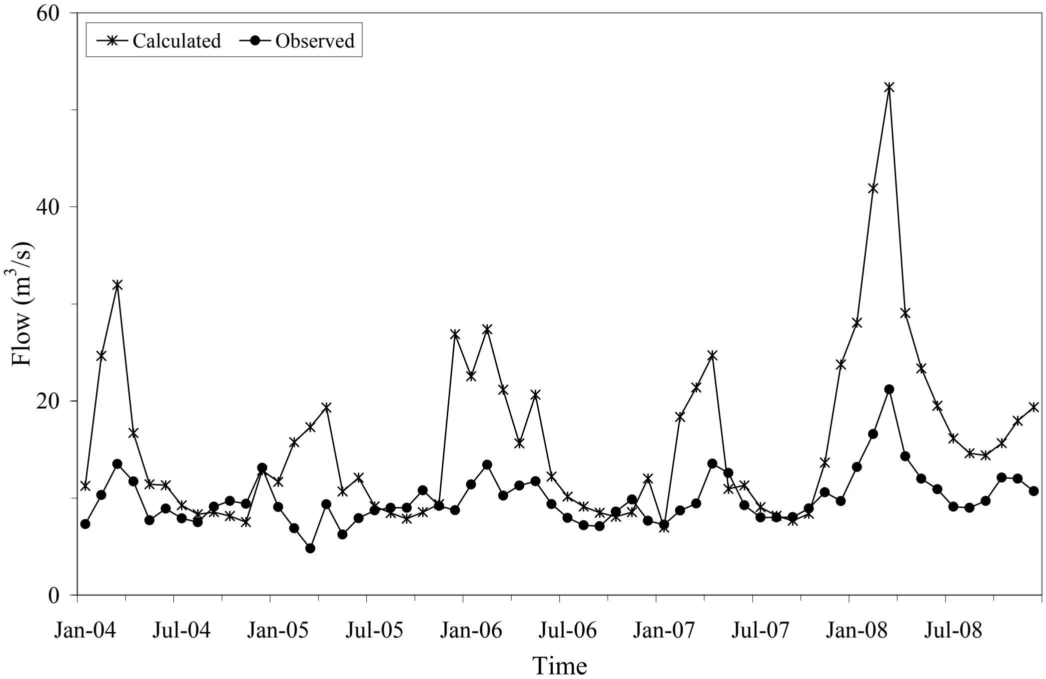

Figure 9.4 Observed and calculated flow of Konto meeting to Brantas

9.6.1.4 Rainfall and evaporation

Last ten years (1999-2008) rainfall data of Karangploso station, which is close to Konto irrigation area is collected from PJT-I and reported in Table 9.5. Annual average rainfall is about 2,700 mm whereas potential evapotranspiration (ET_0) is around 1,450 mm. Monthly ET_0 values are shown in Figure 9.5. Maximum rainfall occurs in the months of February and March (more than 500 mm) and the minimum in August and September (less than 15 mm).

Table 9.5 Past ten year (1999 – 2008) average rainfall (mm) at Karangploso station adjacent to Konto irrigation area

Year	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Annual
1999	750	468	554	465	27	17	11	38	2	348	403	706	3,789
2000	570	689	441	318	199	57	15	53	30	112	335	113	2,932
2001	603	529	610	381	135	209	77	7	16	317	268	0	3,152
2002	635	1,057	344	173	95	0	0	0	0	0	93	276	2,673
2003	274	541	636	83	81	7	0	0	11	20	373	280	2,306
2004	337	661	695	83	4	11	9	0	7	0	161	400	2,368
2005	170	227	288	245	12	131	73	0	33	33	149	619	1,980
2006	542	434	360	120	318	0	0	0	6	0	67	396	2,243
2007	101	481	492	363	89	36	18	21	6	158	289	623	2,677
2008	486	651	837	190	149	32	0	23	0	150	219	323	3,060
Average	447	574	526	242	111	50	20	14	11	114	236	374	2,718

Source: PJT-I database, 2010

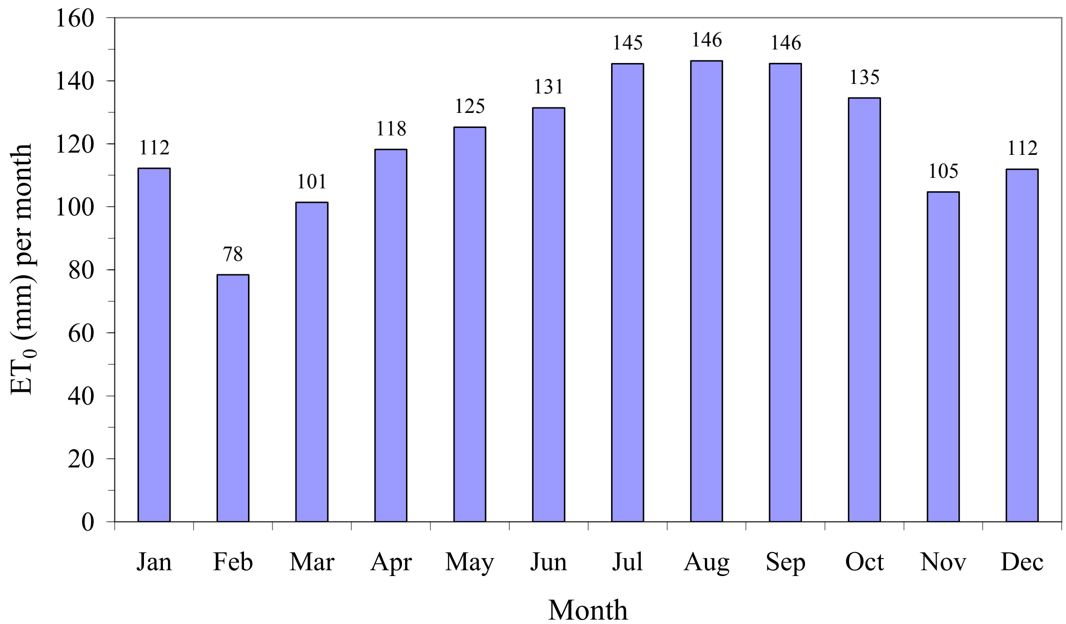

Figure 9.5 Monthly ET_0 (mm) at Karangploso station near Konto irrigation area
Source: PJT-I database, 2010

9.6.2 Data and information related to Selorejo Reservoir

Major features of the Selorejo reservoir are collected from PJT-I and presented in Table 9.6. Selorejo reservoir has a catchment area of 236 km^2. It has a maximum capacity of about $42x10^6$ m^3; however, the effective capacity is $39.59x10^6$ m^3 with an area of 4 km^2. The maximum and minimum operating elevations are 622 and 607 m a.m.s.l. respectively.

Table 9.6 Basic information on Selorejo reservoir

Reservoir		
	Reservoir name	Selorejo
	Drainage Area	236 km^2
	Maximum Capacity (in 2007)	$41.867x10^6$ m^3 (planned $62.3x10^6$ m^3 in 1970)
	Effective capacity (in 2007)	$39.59x10^6$ m^3 (planned $54.6x10^6$ m^3 in 1970)
	Area at effective capacity	4 km^2
	Maximum operating elevation	622 m a.m.s.l
	Dead water elevation	598 m a.m.s.l.
	Minimum operating elevation	607 m a.m.s.l.
	Tail water elevation	582 m a.m.s.l.
Dam		
	Crest length	450 m
	Crest width	8 m
	Crest elevation	625 m a.m.s.l.
	Base Length of dam	312 m
	Height	49 m

Spill-way	
Number of gate	3
Diameter	5.5 m
Discharge capacity	360 m^3/s

Source: PJT-I, 2007

Average monthly release from the Selorejo for the period of 1999 – 2008 is collected from PJT-I and presented in Table 9.7. Average annual release from Selorejo is 10.3 m^3/s. maximum release occurs in the months of February to April (more than 12 m^3/s) and lowest release in July – September (around 8 m^3/s).

Figure 9.6 shows the storage-area-elevation relation for the dam, detail dataset is reported in Appendix F, Table F.4. Release from Selorejo is principally going to the Selorejo power plant. In case when a release higher than the plant capacity is necessary, the extra flow is redirected to the main stream of Konto.

Table 9.7 Average monthly release (m^3/s) from the Selorejo reservoir (1999 - 2008)

Year	**Jan**	**Feb**	**Mar**	**Apr**	**May**	**Jun**	**Jul**	**Aug**	**Sept**	**Oct**	**Nov**	**Dec**	**Annual average**
1999	11.54	14.46	13.38	12.70	9.09	8.74	9.25	8.86	8.60	8.53	8.08	13.96	10.60
2000	14.85	19.52	16.73	15.91	12.13	11.36	9.63	8.95	9.94	10.65	10.90	9.73	12.53
2001	9.95	13.02	12.48	13.65	8.73	10.59	9.25	9.25	9.11	10.15	10.71	9.50	10.53
2002	10.37	22.07	14.63	12.54	9.84	9.23	9.18	9.20	9.10	9.18	8.50	8.68	11.04
2003	9.62	8.22	13.43	6.97	6.91	7.97	6.76	7.65	8.06	8.68	8.89	9.04	8.52
2004	7.27	10.27	13.49	11.74	7.73	8.92	7.94	7.50	9.11	9.72	9.43	13.07	9.68
2005	8.11	6.72	5.85	9.90	5.89	7.50	8.37	8.60	8.61	10.27	8.94	9.10	8.16
2006	11.69	13.18	10.05	11.36	11.15	8.82	7.48	7.50	7.56	9.01	10.02	7.54	9.61
2007	7.58	8.81	9.65	13.88	8.15	9.40	8.50	8.50	8.57	9.25	10.67	10.48	9.45
2008	14.19	16.42	19.53	14.85	12.02	10.33	9.25	9.25	10.00	11.91	12.16	10.97	12.57
Monthly Average	10.52	13.27	12.92	12.35	9.16	9.29	8.56	8.53	8.87	9.74	9.83	10.21	

Source: PJT-I database, 2010

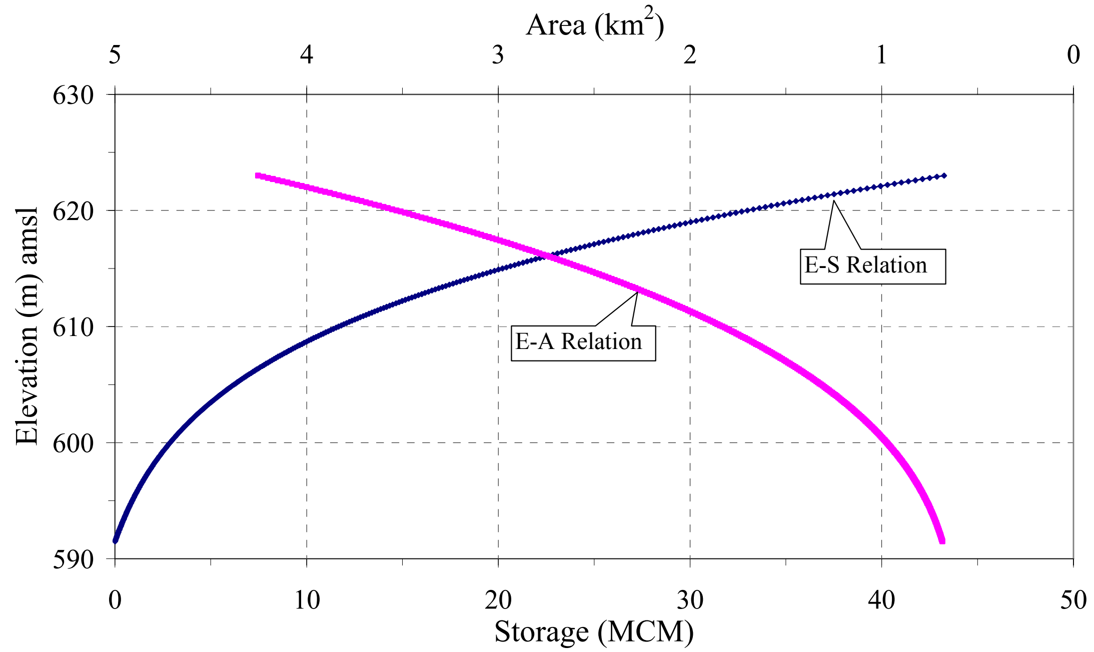

Figure 9.6 Storage (S)–Area (A)–Elevation (E) relationship for the Selorejo reservoir
Source: Based on data obtained from PJT-I database, 2010

9.6.3 Hydropower and power production

Three hydropower plants, namely: Selorejo, Mendalan and Siman are operating in the study basin as mentioned earlier. Basic information related to power plant such as installed capacity, design discharge, effective head and power production information is collected from PJT-I. Efficiencies of the plants are estimated as part of the project of this study. Table 9.8 presents the basic information related to the plants. Monthly power production data for last ten years (1999 - 2008) for Selorejo plant and for last six years (2003 – 2008) for Mendalan and Siman plants are presented in Appendix F, Table F.5. Mendalan plant has the maximum effective head of 150.2 m among the three plants; however, maximum overall efficiency of 0.82 is estimated for Selorejo plant. Average annual power productions from Selorejo, Mendalan and Siman power plants are respectively 23,939, 76,881 and 55,646 MWh.

Table 9.8 Basic information on hydropower plants in Konto River Basin

Hydropower plant	**Installed capacity (MW)**	**Design discharge (m^3/s)**	**Effective head (m)**	**Overall efficiency***	**Average Annual energy production (MWh)**
Selorejo	4.5	14.9	35.2[a]	0.82	23,939
Mendalan	7.0	8.5	150.2	0.73	76,881
Siman	9.0	8.5	106.4	0.74	55,646

Note: [a] Average water elevation in the reservoir is taken as 617.2m whereas tail water elevation is 582m a.m.s.l.
Source: PJT-I, 2007; *Triweko et al. (2010)

9.6.4 Reservoir fishery and recreation

Fish production data was collected from the Department of Fisheries (DoF) at Malang; however, only three years (2008 – 2010) monthly fish production data was available at the DoF office. The production information is based on region specific e.g. Malang and shown as source specific e.g. river, lake, reservoir, swamp etc. Not exactly from Selorejo reservoir, rather overall fish production from reservoirs in Malang is obtained from DoF. Malang has only two main reservoirs that produce fish and they are almost same in size. Therefore, half of the production data obtained for reservoirs is considered as fish production from Selorejo reservoir. Table 9.9 presents the fish production data from Selorejo. Average monthly fish production is around only 10 tonnes (113.5 tonnes annually) from the Selorejo reservoir. Monthly average fish production is plotted against monthly Selorejo storage and presented in Figure 9.7. However, the data range is too short to draw some statistical interpretation.

Table 9.9 Monthly fish production (tonne) from Selorejo reservoir

Year	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Annual total
2008	5.39	6.02	3.09	5.29	2.09	1.89	12.42	4.59	1.57	4.43	5.65	7.93	60.36
2009	13.23	20.34	19.92	14.62	16.30	12.48	2.78	3.00	2.15	8.63	7.47	11.67	132.59
2010	12.93	13.97	12.31	14.41	14.36	10.81	10.86	10.23	11.06	11.31	11.94	13.35	147.54
Avg	10.52	13.44	11.77	11.44	10.92	8.39	8.69	5.94	4.93	8.12	8.35	10.98	113.49

Source: DoF, Malang, 2010

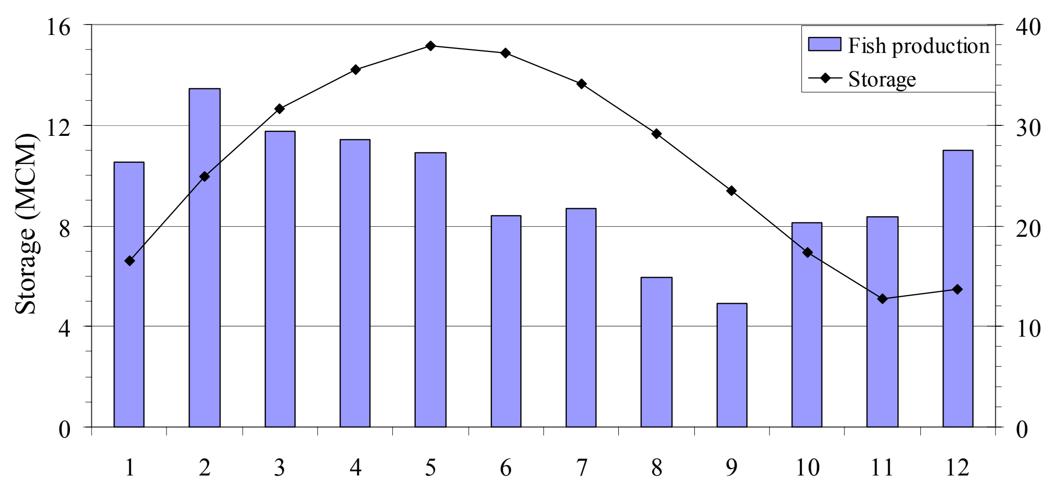

Figure 9.7 Average monthly fish production from Selorejo reservoir and corresponding Selorejo storage

Due to its natural beauty, Selorejo reservoir attracts tourists from inside and outside Malang. The beauty of the dam which is surrounded by hills and mountains namely Mount Anjasmoro, Mount Kelud, and Mount Kawi, those add air coolness that can be felt. The average temperature of 22^{0}C makes people feel at home there. The site is mainly used for sight seeing; however, boating and skiing are also done by the recreationists. Monthly number of recreationists to the Selorejo reservoir was collected from PJT-I. PJT-I has the data only for the period of 2001 to 2008, which is reported in Table 9.10. Average annual number of recreationists is about 173,215 at the reservoir site. Maximum number of tourists are found in the month of July (dry season) whereas the lowest in February (wet season). February is the month with highest rainfall, which is probably the reason for less number of recreationists. On the other hand, June-July is the school holiday time, which might affects the recreational activities and results highest number of tourists in June and July. The number of tourists are plotted against Selorejo reservoir storage and presented in Figure 9.8. However, no significant relation is found between reservoir storage and number of tourists visiting the reservoir site.

Table 9.10 Monthly numbers of recreationists to the Selorejo reservoir

Year	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
2001	17,069	8,359	15,358	10,611	13,736	22,322	20,851	11,156	13,151	15,757	8,312	17,482
2002	18,671	8,964	13,551	12,275	13,076	21,390	18,642	10,385	10,593	11,472	3,995	26,507
2003	18,743	6,621	6,661	11,874	14,615	16,749	18,246	10,557	9,691	9,078	13,045	19,906
2004	11,412	8,554	8,043	10,157	13,776	19,428	19,721	13,200	12,388	6,589	23,655	11,240
2005	22,666	10,780	10,408	11,513	14,011	18,567	26,698	11,349	14,730	4,051	28,226	10,068
2006	19,047	4,942	9,191	13,292	12,329	22,482	26,985	14,719	11,698	13,801	13,691	16,154
2007	19,538	7,668	12,186	10,801	17,929	23,136	23,716	15,549	8,371	13,262	11,185	17,023
2008	23,409	10,340	13,073	9,434	16,543	18,917	22,886	13,093	13,590	13,324	13,213	18,495
Avg	18,819	8,279	11,059	11,245	14,502	20,374	22,218	12,501	11,777	10,917	14,415	17,109

Source: PJT-I Database, 2010

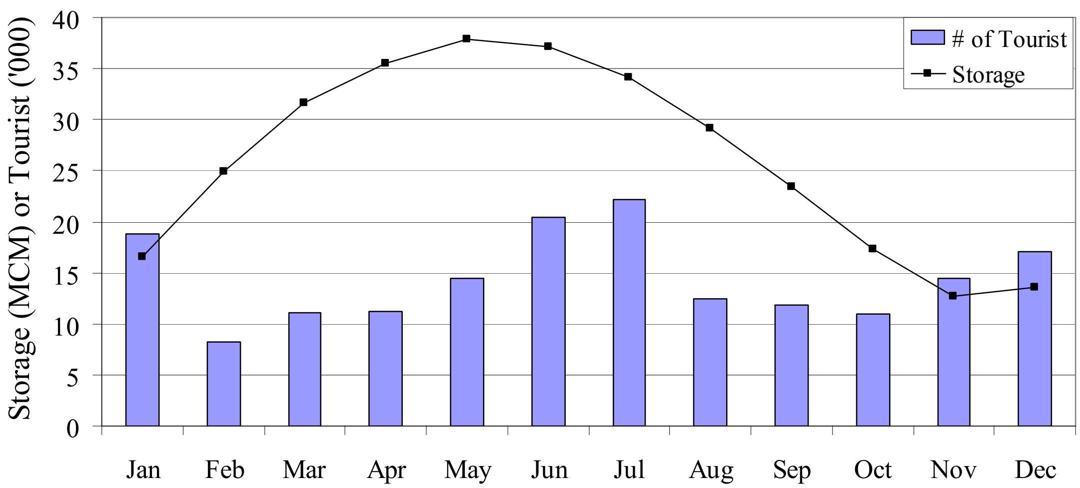

Figure 9.8 Average monthly number of tourists at Selorejo reservoir and corresponding Selorejo storage

9.6.5 Agricultural data

The agricultural economy of the basin is centered on the cultivation of paddy, nearly all of which is low land rice and irrigated. More than half of all paddy produced in Indonesia is harvested on Java. Javanese rice yield is about 15 percent higher than the overall Indonesian average mainly due to good irrigation system, favorable soils and climate along with historical experience in paddy cultivation in the region (Rodgers and Hellegers, 2005). Other crops include coffee, cassava, maize, peanuts, soybeans, sugarcane, and tobacco. The irrigated dry season crop including maize, soybeans and peanuts, are collectively known as *Palawija*. The prevalent rotation in the Konto basin is paddy-paddy-*palawija*. Three seasons are predominant in agricultural practices; namely: wet season (November – February), first dry season (March – June) and second dry season (July – October).

Data related to agricultural practices, land use, crop calendar, climate and crop production are collected from secondary sources, mainly from the reports made available by PJT-I. Detailed data is reported in the next chapter in Section 10.2.2.

9.6.6 Economic data

To estimate the benefit for each of the water uses, economic data was collected as listed:

- Water tariff to be paid by PJB to PJT-I for production of hydropower (obtained from PJB)
- Agricultural input and output price (farm gate price obtained from PJT-I)
- Fish price (market price as obtained from DoF, Malang)
- Entrance fee to the reservoir for recreational purpose (obtained from PJT-I)

Details on all these data and information are provided in the next chapter where the economic benefit functions are established.

9.7 Estimation of environmental flow

Information related to flow in the Konto at natural condition i.e. the flow before commissioning Selorejo reservoir on 1970 is not available from any source. However, inflow to Selorejo is calculated by PJT-I using water level in the reservoir and past ten years (1999 – 2008) mean monthly inflow data was made available for the study by PJT-I. In addition, for the period of 2004 – 2008 the mean monthly flow of Konto that meets with Brantas is obtained from PJT-I. The monthly flow of the three tributaries to Konto, namely: Sambong, Nogo and Nambaan rivers are estimated as part of this research by Triweko et al. (2010). Based on all these data, the virgin flow of Konto is estimated and EF requirements for the river are assessed for two locations, namely: at Mendalan *Sabo* dam (after abstraction to Siman daily retention pond) and at the last downstream point of Konto before it meets Brantas.

9.7.1 EF at Mendalan *Sabo* dam

The inflow to Selorejo can suitably be considered as the natural flow in the Konto up to Selorejo dam if the reservoir would not been there. At the downstream of Selorejo dam, three very small (in terms of flow) tributaries met with the Konto (as shown in Figure 9.3). Up to Mendalan *Sabo* dam, the length of Konto is about eight km. At this *Sabo* dam point, there is a water abstraction structure with the capacity of 2 – 3 m^3/s to Siman daily retention pond to stabilize the flow to Siman power plant. Environmental flow requirements are considered at the downstream point to Mendalan *Sabo* dam point after abstraction for Siman daily retention pond.

Environmental flow is estimated based on the inflow to Selorejo (as reported in Table 9.3) with the addition of flow of the Sambong, Nogo and Nambaan river that meets to Konto before Mendalan *Sabo* dam point (as reported in Table F.1 of Appendix F). Scope of this study is kept limited within estimation of EF by hydrological methods. However, several hydrological methods are available as discussed in Section 2.3.4. Three different hydrological methods, namely: Tennant method, FDC method and RVA method was applied for the case of Teesta, the other study site of this research. Average daily flow data at least for 20 years is required to estimate EF using FDC and RVA method. On the other hand, Tennant method is based on mean annual flow (MAF). In case of Konto, only ten years average monthly flow data is available, which gives MAF for using Tennant method. The mean annual flow (MAF) for the Konto at Mendalan *Sabo* dam point is estimated to be 10.74 m^3/s (based on data for 1999 – 2008). The EF requirements based on Tennant method are then presented in Table 9.11.

Table 9.11 Environmental flow requirements for the Konto at Mendalan *Sabo* dam point based on Tennant method

Environmental status as defined by Tennant	EF requirement (m^3/s)	
	High flow season (November - April)	**Low flow season (May - October)**
Flushing flow	20.48 (200%)	20.48 (200%)
Optimum range	6.44 – 10.74 (60 – 100%)	6.44 – 10.74 (60 – 100%)
Outstanding	6.44 (60%)	4.30 (40%)
Excellent	5.37 (50%)	3.22 (30%)
Good	4.30 (40%)	2.15 (20%)
Fair or degrading	3.22 (30%)	1.07 (10%)
Poor	1.07 (10%)	1.07 (10%)
Severe degradation	<1.07 (<10%)	<1.07 (<10%)

MAF= mean annual flow; values in parenthesis are the percentage of MAF

Based on Tennant method to maintain a 'good' environmental (habitat) status, high flow season requires a flow of 4.30 m^3/s where as low flow season needs a flow of 2.15 m^3/s. If the authority choices one status down to 'good' that is 'fair or degrading' status, then it needs 3.22 m^3/s flow for high flow season and 1.07 m^3/s flow for the low flow season. In case a 'poor' status is opted for, 1.07 m^3/s flow needs to be maintained all the year round.

9.7.2 EF above the confluence with Brantas

Estimating EF just above the confluence of Konto with Brantas requires the virgin flow of the basin. After the abstraction of water to Siman daily retention pond at Mendalan *Sabo* dam, no other major abstraction exists at the downstream part of the Konto except 0.7 m^3/s of M&I supply. Flow at Mendalan *Sabo* dam point is available from the simulation of the hydrological system carried out as part of this research and reported by Triweko et al. (2010). Flows of Konto draining to Brantas for five years are known from PJT-I (2010a). Summing up the inflow to Selorejo, observed flow of Konto draining to Brantas and M&I supply with deduction of flow at Mendalan *Sabo* dam generate the Konto original flow. Detailed dataset is reported in Appendix F, Table F.6.

Based on the estimate given in Table F.6, the mean annual flow (MAF) for the Konto River is 18.77 m^3/s. Using Tennant method the EF requirements for the Konto basin is estimated and documented in Table 9.12.

Table 9.12 Environmental flow requirements for the entire Konto river basin based on Tennant method

Environmental status as defined by Tennant	**EF requirement (m^3/s)**	
	High flow season (November - April)	**Low flow season (May - October)**
Flushing flow	37.54 (200%)	37.54 (200%)
Optimum range	11.26 – 18.77 (60 – 100%)	11.26 – 18.77 (60 – 100%)
Outstanding	11.26 (60%)	7.51 (40%)
Excellent	9.38 (50%)	5.63 (30%)
Good	7.51 (40%)	3.75 (20%)
Fair or degrading	5.63 (30%)	1.87 (10%)
Poor	1.87 (10%)	1.87 (10%)
Severe degradation	<1.87 (<10%)	<1.87 (<10%)

MAF= mean annual flow; values in parenthesis are the percentage of MAF

To maintain a 'good' environmental (habitat) status as defined by Tennant, high flow season requires a flow of 7.51 m^3/s where as low flow season needs a flow of 3.75 m^3/s. If the authority choices one status down to 'good' that is 'fair or degrading' status, then it needs 5.63 m^3/s flow for high flow season and 1.87 m^3/s flow for the low flow season. In case a 'poor' status is opted for, 1.87 m^3/s flow needs to be maintained all the year round.

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10 BENEFIT FUNCTIONS OF WATER USES IN THE KONTO RIVER BASIN

This chapter describes and estimates the benefit functions of water uses in the Konto using the concept, methodology and application as described in Part-I, Chapter 3 and Part-II, Chapters 5 and 6. To avoid the repetition, only empirical assessment of the benefit functions of the water uses are described in this chapter with reference to previous chapters.

10.1 Hydropower

Benefit from water used in power production is estimated using Equation 3-4 and Equation 3-5. Since, no information was available related to the peak, off-peak and at night operation time and related power production, a constant slope total benefit function i.e. a horizontal marginal benefit function is established using the water price for energy production that is paid by PJB to PJT-I. Currently the price is US$ 21.76 per MWh (IDR 196 per kWh).

The energy rate functions, *erf* (kWh/m^3) and subsequently the benefit functions for the three hydropower stations have been estimated and presented in Table 10.1.

Table 10.1 Energy rate functions and marginal benefit functions for the three hydropower plants in Konto river basin

Hydropower plant	**Energy rate function, *erf* (kWh/m^3)**	**Marginal benefit for water (US$/10^3 m^3)**
Selorejo	$erf_{sel} = \frac{1}{367} * 0.82 * h$ = 0.079 (considering average observed effective head, h = 35.2 m)	$MB_{Sel} = 1.72$
Mendalan	$erf_{Mndl} = \frac{1}{367} * 0.73 * h$ = 0.299 (considering effective head, h = 150.2 m)	$MB_{Mndl} = 6.50$
Siman	$erf_{siman} = \frac{1}{367} * 0.74 * h$ = 0.215 (considering effective head, h = 106.4 m)	$MB_{Siman} = 4.67$

Mendalan plant has the highest effective head among the three plants and it produces the maximum marginal benefit of US$ 6.5 per 10^3 m^3 of water. Selorejo plant generates the lowest marginal benefit of US$ 1.72 per 10^3 m^3 of water.

10.2 Irrigation

10.2.1 Irrigation water pricing

Farmers using irrigation water in the Brantas currently do not pay a volumetric tariff for water; however, they pay an irrigation service fee (ISF) payable to local Water User Association (WUA). PJT-I recovers recurring costs from the higher tariffs from municipal and industrial water supplies that has a double edge, i.e. farmers get water in a low cost, however, when water is scarce, farmers are the first to see supplies curtailed (Subijanto et al., 2009). The ISF is placed only to generate operating funds for system maintenance and rehabilitation. ISF is based on flat, area-based fee calibrated to reflect (i) desired level of O&M, (ii) land productivity and (iii) the ability of farmers to pay. Currently ISF per hectare of land and per season falls in the range of US$1.4–1.6 (IDR 12,000–14,000) for wetland crops, mostly rice, and a lesser amount for dry-footed crops. Most of the irrigated crops in the second dry season are considered unauthorized, that is, they do not necessarily receive required irrigation water to maintain their crops. Since farmers are not currently paying for bulk-water deliveries and they do not have license, they are not compensated if they receive less water for their crops. Such a situation happened in Citarum Basin in West Java in 2003 drought when canal-full water was passing to Jakarta leaving the agricultural lands dry and farmers had to watch without any recourse for the imposed rationing system, apart from social unrest (Rodgers and Hellegers, 2005).

10.2.2 Data and methods

10.2.2.1 Irrigation water requirement

Land use and cropping pattern at Konto irrigation area

Information of the current land use and cropping patterns are collected from PJT-I. Rice in three seasons (Dry-1, Dry-2 and Wet) and *Palawija* in two seasons (Dry-1 and Dry-2) mainly are grown in Konto irrigation area that includes Srinjing irrigation area and right Konto irrigation area as shown in Figure 9.3. The crops grown in different seasons and area irrigated for each crop are documented in Table 10.2. Figure 10.1 shows the crop calendar for irrigated crops at the Konto Irrigation Project.

Table 10.2 Agricultural land use patterns at Konto irrigation area

Season (Duration)	**Crop 1**			**Crop 2**		
	Crop	**Cropped area (ha)**	**% of net area**	**Crop**	**Cropped area (ha)**	**% of net area**
Dry-1 (March – June)	Paddy	11,835	39	*Palawija*	10,638	70
Dry-2 (July – October)	Paddy	2,438	8	*Palawija*	21,336	35
Wet (November - February)	Paddy	23,275	77	----	----	
Total cropped area (ha)		69,522				
Net area (ha)		30,431				
Crop intensity (%)		2.28				

Source: PJT, 2010

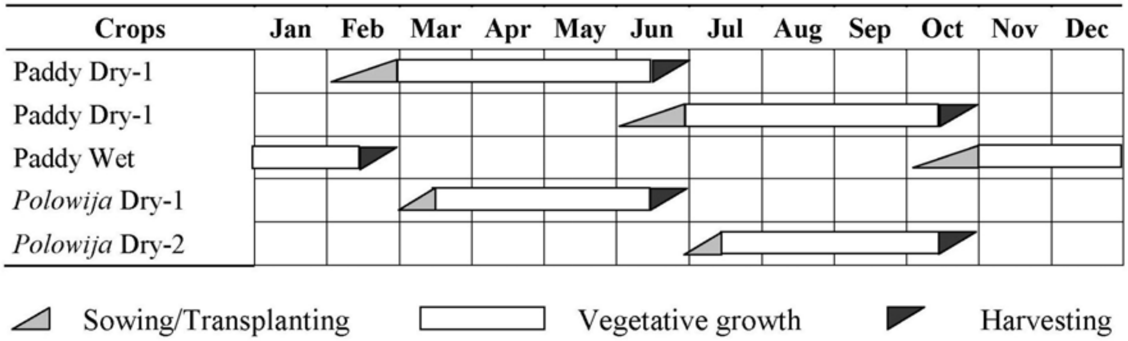

Figure 10.1 Crop calendar for Konto Irrigation Project
Source: PJT-I, 2007

Potential evapotranspiration (ET_0)

Potential evapotranspiration is calculated with Penman-Montieth method. Using the climatic dataset for the closest station, Karangploso of the irrigation area, the potential evapotranspiration is calculated and reported in Table 10.3.

Table 10.3 Climatic data and ET_0 at Konto Irrigation Project

Month	Avg Temp (^{o}C)	Humidity (%)	Wind speed (km/d)	Sunshine (h)	Solar radiation (MJ/m^2/d)	ET_0 (mm/d)
January	24.5	75	74	7.2	18.5	***3.62***
February	23.1	80	79	3.0	13.3	***2.80***
March	23.3	82	160	4.1	15.6	***3.27***
April	23.1	78	168	6.5	19.5	***3.94***
May	23.0	79	225	7.4	20.3	***4.04***
June	23.1	80	242	8.7	23.2	***4.38***
July	22.7	76	352	10.1	24.0	***4.69***
August	23.9	82	256	10.7	25.5	***4.72***
September	23.8	83	307	11.5	27.0	***4.85***
October	23.8	82	259	9.5	23.2	***4.34***
November	24.0	81	67	7.0	18.3	***3.49***
December	23.8	81	74	7.2	18.0	***3.61***

Source: PJT-I database, 2010

Seepage & percolation (S&P) rate

Seepage (S), the lateral subsurface flow of water from a bunded rice field and percolation (P), the downward flow of water below the root zone occur simultaneously during land preparation and crop growth period and are governed by the water head (depth of pounded water) on the field and the resistance to water movement in the soil. Due to the difficulty in separation between seepage and percolation in the field, S and P are often taken together as one term, S&P. The S&P value for Konto irrigation area is considered as 2 mm/d as used in earlier studies (e.g. PJT-I, 2007).

Mean aerial Rainfall

Past ten years (1999 – 2008) rainfall data collected at Karangploso station as documented in Table 9.5 is used for irrigation water requirements calculations.

Irrigation requirement

Irrigation water requirements for *Palawija* crops are estimated using CROPWAT model version 4.3 (FAO, 1998). Since rice is not included in CROPWAT 4.3, similar approach of field water balance as mentioned in Chapter 5, Equation 5-1 is employed to estimate the irrigation water requirement for paddy. All the rice types in the project area are considered to be of lowland type. In the water balance approach S&P loss (2 mm/d) is assumed to occur for the first 105 days when the ponding condition exists and afterwards the rice field is drained for last 15 days where the total growth period of the rice crops are considered 120 days. Ponding depth in rice field is assumed to be at least 50 mm with a maximum up to 100 mm. In case of excess rainfall beyond the field-bund capacity, the excess rainwater goes out from the system as runoff. In addition, water requirement for nursery (nursery is assumed as 5% of respective rice area cultivated) and land preparation are accounted for. Crop coefficient of rice for different stages of crop growth and corresponding length in days are used as mentioned in Table 10.4.

Water requirement for land preparation

Water requirement for land preparation for rice at the Konto irrigation area is assumed 180 mm for a period of 20 days i.e. 9 mm/d.

Table 10.4 Crop coefficient and duration of different stages of rice and *Palawija* crop

Stage	**Length (day)**		**Crop coefficient**	
	Rice	***Palawija***	**Rice**	***Palawija***
Land preparation	20	---	---	---
Nursery	30	---	1.20	---
Initial stage	20	20	1.10	0.45
Development stage	30	30	1.10 – 1.25	0.45 – 1.00
Mid season	40	40	1.25	1.00
Late season	30	30	1.25 – 1.00	1.00 – 0.45
Total	120	120		

Source: Solihah, 2011

Irrigation efficiency

Two measures of water are dealt, namely: water use requirement at field (WRF) which is the actual irrigation requirement for plants at the field level and water withdrawal requirement from the source (WWR). Water withdrawal requirement would be always higher than WRF due to several losses. The ratio of WRF to WWR is defined as the overall efficiency of the irrigation project. For the Konto irrigation area, overall irrigation efficiency (including conveyance, field channel and field application) is considered to be 55% based on several studies (e.g. Rodgers and Hellegers, 2005) for the Brantas basin.

10.2.2.2 Irrigation water value using Residual Imputation Method

Irrigation water value for the Konto Irrigation area is estimated using RIM. The theory of RIM is already described and discussed in Chapter 5 under Section 5.2.2. Residual imputation method accounts for the incremental contribution of each input in a production process. In the market with competitive equilibrium, when correct prices – equal to their marginal returns – are assigned to all input resources used in production process except one (water in this particular case), the remainder of total value of the product is imputed to the remaining or the residual input resource (Young, 1996; Agudelo, 2001). Inputs for agricultural production are considered as labor, tractor, seed, fertilizer, pesticide and equipments. Information on the quantities of inputs for and output from the crop production process are mainly collected through PJT-I. Market prices as of December 2010 for the agricultural inputs and outputs are considered in the residual imputation analyses.

10.2.2.3 Total and marginal benefit function

Similar approach as mentioned in Chapter 5 is again adopted here. Yield response to water stress due to five different levels of hypothetical water shortage form the basis in estimating the total and marginal benefit functions for irrigation water. Residual imputation method gives the irrigation water value for each level of water shortage. Yield loss for the *Palawija* crops are estimated using Equation 5-4 whereas for rice Equation 5-5 is used. Potential yield values (Y_{max}) are taken from Rodgers and Hellegers, 2005.

10.2.3 Results and discussion

10.2.3.1 Irrigation water use requirements

Dry season six months (May - October) mainly need irrigation supply. Table 10.5 presents the net irrigation water requirements at field along with the effective rainfall for paddy and *Palawija*. Paddy in Dry-1 and wet season needs less amount of irrigation water of 230 and 214 mm respectively in compare to Paddy in dry-2 season, which needs as much as 1,080 mm of irrigation supply. In dry-2 season rainfall amount is very small, which results higher irrigation demand.

In case of rice, the effective rainfall is estimated from the field water balance study (Equation 5-1) pertaining to maintain the ponding condition in the field after transplantation of the rice plants. Effective rainfall for other crops is estimated using the USDA soil conservation service method embedded in the CROPWAT modeling.

Table 10.5 Water use requirement at field (WRF) (mm) for rice and *Palawija* crops grown in the Konto irrigation area

Crops (growing period)		**Water requirement at field and effective rainfall**			
		Total WRF	**Effective rainfall**	**Net WRF**	**Sum**
Paddy Dry-1	Nursery	114	436	0	
(D1 Feb – D3 Jun)	LP	180	294	0	
	Growing stage	810	580	230	230
Paddy Dry-2	Nursery	162	11	151	
(D1 Jun – D3 Oct)	LP	180	7	173	
	Growing stage	905	149	756	1,080
Paddy Wet	Nursery	152	88	64	
(D1 Oct – D3 Feb)	LP	180	70	110	
	Growing stage	750	710	40	214
Palawija Dry-1 (D1 Mar – D3 Jun)	Growing stage	541	419	122	122
Palawija Dry-2 (D1 July – D3 October)	Growing stage	440	108	332	332

LP = Land preparation; CWR= Crop water requirement including the water requirements to maintain ponding condition; D1, D2 and D3 are 1-10, 11-20 and 21-30 dates of each month

Table 10.6 presents the WRF and WWR in monthly basis and by crop wise. Total irrigation water requirement at field is calculated to be 464 mm. Considering the overall irrigation efficiency of 55% (ADB/IFPRI (2003) reported the overall efficiency for Konto irrigation system is 0.53 – 0.59), water withdrawal requirements stands for 843 mm.

Table 10.6 Irrigation Water Requirement (mm) for all Crops and By Months

Month	**Paddy Dry-1**	**Paddy Dry-2**	**Paddy Wet**	***Palawija* Dry-1**	***Palawija* Dry-2**	**Total WRF**	**Total WWR**
Area under crop (%)	39	8	77	35	70		
May	75	0	0	47	0	45	83
June	155	325	0	75	0	88	160
July	0	220	0	0	50	53	96
August	0	239	0	0	130	110	201
September	0	225	0	0	132	110	201
October	0	72	213	0	20	57	104
Sum	230	1,081	213	122	332	464	843

WRF=Water requirement at Field; WDR=Water diversion requirement

10.2.3.2 Value of water for irrigation

The value of irrigation water is estimated based on residual imputation method and the results are presented in Table 10.7 for each crop. The details of the RIM calculation with each input output price is reported in Tables G.1 and G.2 of Appendix G. The value of water value estimation presented in Table10.7 considers no-water-stress to the crops implying highest possible yield. Among all the crops grown in the Konto irrigation project area using irrigation water, Paddy Dry-1 generates the highest irrigation-water value of US$ 86 per 10^3 m^3 of water (IDR 777 per m^3). Due to less rainfall, paddy grown in the second dry season requires the largest part of irrigation water and results in the lowest irrigation water value of US$ 24 per 10^3 m^3 of irrigation water (IDR 214 per m^3). The average value of water for irrigation is estimated as US$ 65 per 10^3 m^3 (IDR 584 per m^3) of water diverted and US$ 117 per 10^3 m^3 (IDR 1,061 per m^3) of water used at field level.

Table 10.7 Value of irrigation water for different crops grown in Konto irrigation project

Crops	**Area irrigated (ha)**	**Input cost (US$/ha)**	**Yield (t/ha)**	**Harvest value (US$/ha)**	**WWR (m^3/ha)**	**Value of water (US$/ $10^3 m^3$)**
Paddy Dry-1	11,835	958	5.4	1,319	4,184	86
Paddy Dry-2	2,438	975	5.9	1,441	19,645	24
Paddy wet	23,275	1005	5.1	1,246	3,876	62
Palawija Dry-1	10,638	689	2.25	875	2,224	84
Palawija Dry-2	21,336	704	2.25	875	6,045	28
Average value of withdrawn irrigation water						65
Average value of irrigation water used at field level						117

10.2.3.3 Total and Marginal benefit functions

Following RIM, the overall benefit from agricultural production using irrigation water at the Konto irrigation site is calculated for five different water shortage levels. Total benefits is distributed over the irrigation season uniformly and considered on monthly basis. Water availability is further reported as the mean flow over six months of the irrigation period. Table 10.8 represents the water availability and monthly benefit at different water shortage levels. Using the water availability and monthly benefits in the quadratic function (Equation 3-1) the total benefit function from irrigation water is established. Equations 10-1 and 10-2 present the total and marginal benefit function for the irrigation water use in monthly basis. Values of TB and MB in Equations 10-1 and 10-2 respectively are in million US$ per month. The total and marginal benefit function is also presented in Figure 10.2.

$$TB = -0.0009*flow^2 + 0.2033*flow - 0.3456 \qquad (10\text{-}1)$$

$$MB = -0.0018*flow + 0.2033 \qquad (10\text{-}2)$$

Table 10.8 Average monthly benefits to be imputed to withdrawn irrigation water at different water shortage levels

	Water shortage in % of water withdrawal requirement					
	0%	**10%**	**20%**	**30%**	**40%**	**50%**
Water availability m^3/s (mm)	16.5 (844)	14.9 (759)	13.2 (675)	11.6 (591)	9.9 (506)	8.3 (422)
Benefit (10^6 US$)	2.771	2.476	2.184	1.887	1.583	1.271

Analyses based on residual imputation method indicate that the average value of supplied irrigation water for Konto irrigation project, IDR 584 per m^3 is much higher than the currently practiced irrigation service fee (ISF) of IDR 5.0 per m^3 considering IDR 42,000 (3 seasons*IDR 14,000 per season) is paid for 8,430 m^3 of diverted irrigation water per hectare of land per year.

An average monthly flow of 16.5 m^3/s meets fully the irrigation demand and generates the maximum total benefit of US$ 16.62 million (IDR 149.66 billion) from the whole irrigation season, which generates a monthly benefit of US$ 2.771 million (IDR 24.95 billion). At the full supply level the marginal benefit is about US$ 0.174 million per month per m^3/s. The marginal benefit would become US$ 0.188 million per month per m^3/s when the flow decreased to half (8.25 m^3/s).

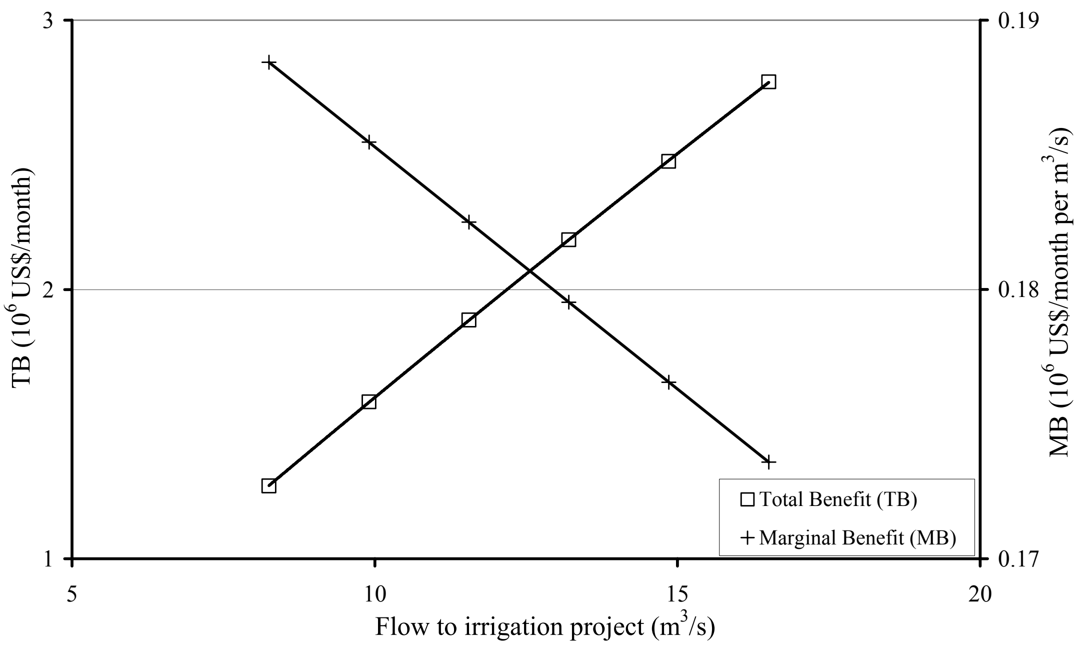

Figure 10.2 Total and marginal benefit functions for irrigation water use in the Konto irrigation project

10.3 Reservoir recreation and fishery

10.3.1 Reservoir recreation

The number of tourists visiting Selorejo reservoir is already reported in Tables 9.10. In estimating the total benefit from reservoir recreation a travel cost approach is considered; however, no information and data is available regarding the travel of the tourists to the Selorejo reservoir site. Based on personal communication to the PJT-I officials establishing the benefit function for recreation is attempted. According to PJT-I officials, Selorejo reservoir attracts mainly the local tourists where 50% normally do not stay overnight at the reservoir site. Average travel distance is considered 40 km, four persons in a vehicle and 10 km per liter of fuel (petrol; IDR 5,000/liter) give an average fuel cost of IDR 5,000 per capita. Considering average one meal per person of IDR 10,000 with an entrance fee of IDR 7,300 per person as provided by PJT-I generate a total benefit of IDR

5,000+10,000+7,300 = 22,300 (US$ 2.5) for a person who does not stay overnight at the Selorejo reservoir site. Opportunity cost of leisure time is considered zero, which is contended by some researchers even though some researchers accounted the opportunity cost of time in different formats as mentioned by Young (2005). Average accommodation charge at the Selorejo site is around IDR 150,000 per person per night which gives the benefit of IDR 178,300 including two more meals (US$ 19.8) for the tourists who stay overnight at the site. Table 10.9 presents average monthly number of tourists based on past eight years data as reported in Table 9.10 and related their benefits. Average monthly benefit from Selorejo reservoir site recreation is about US$ 160×10^3. Maximum benefit is observed in July, which is almost US$ 250×10^3, whereas minimum benefit generating month is February with the benefit value of US$ 92×10^3. Corresponding storages in Selorejo are 34.11×10^6 m^3 in July and 24.91×10^6 m^3 for February. Minimum storage in Selorejo normally occurs in the month of November when benefit for recreation is about US$ 160×10^3.

Table 10.9 Average monthly storage of Selorejo reservoir, number of tourists and related benefits

Month	**Selorejo Storage (10^6 m^3)**	**N^o of tourists**	**Recreational benefit (10^3 US$)**
January	16.55	18,819	209.62
February	24.91	8,279	92.21
March	31.65	11,059	123.18
April	35.46	11,245	125.25
May	37.90	14,502	161.53
June	37.19	20,374	226.93
July	34.11	22,218	247.47
August	29.19	12,501	139.24
September	23.47	11,777	131.17
October	17.32	10,917	121.59
November	12.76	14,415	160.56
December	13.63	17,109	190.57
Average	26.18	14,435	160.78

Source: PJT-I database, 2010

Average monthly number of tourists visiting Selorejo site is plotted against the average monthly Selorejo storage and presented in Figure 10.3. A concave shape function is observed (r^2 = 0.27) which indicates high and low storages in Selorejo attract higher number of tourists compare to medium storage. However, seasonal and few other factors (e.g. end of school vacation) might affect on recreational activity, which has not been explored within the scope of this research.

10.3.2 Reservoir fishery

Past three years (2008 – 2010) monthly fish production from Selorejo is estimated from the data and information obtained from DoF, Malang, which has already been reported in Table 9.9. Fish price information is also obtained from DoF, Malang. Benefit from fish production in detail is documented in Appendix G Tables G.3 and G.4. Table 10.10

presents the average monthly Selorejo storage and corresponding fish production and their benefits.

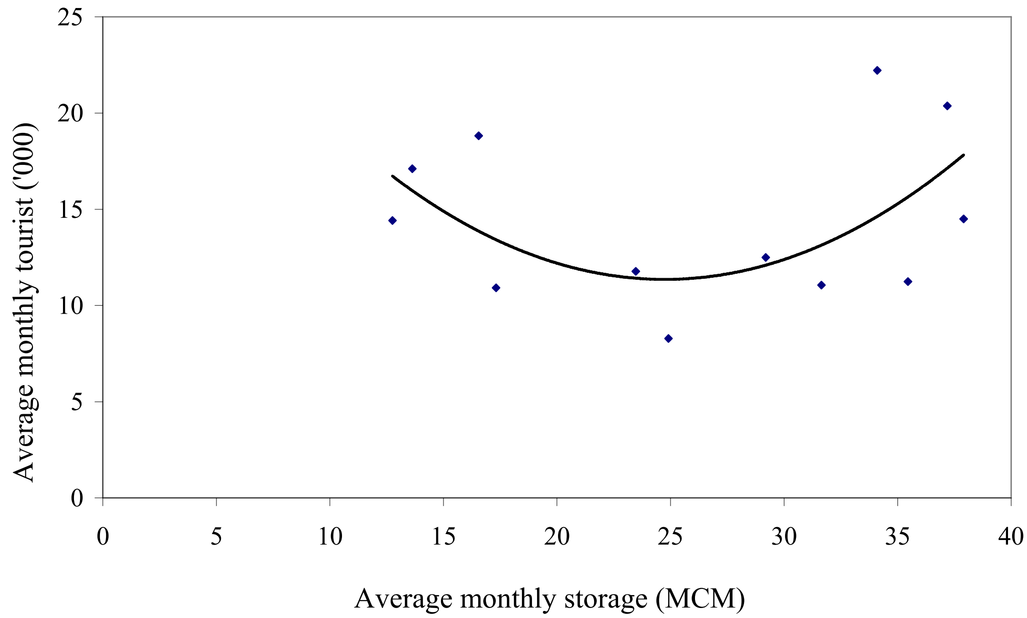

Figure 10.3 Monthly average Selorejo reservoir storage and number of tourists

Table 10.10 Average monthly storage of Selorejo reservoir, fish production and related benefits

Month	**Selorejo Storage (10^6 m^3)**	**Fish production (t)**	**Fishery Benefit (10^3 US$)**
January	16.55	10.52	11.08
February	24.91	13.44	14.35
March	31.65	11.77	12.56
April	35.46	11.44	12.21
May	37.90	10.92	11.42
June	37.19	8.39	8.79
July	34.11	8.69	8.81
August	29.19	5.94	6.06
September	23.47	4.93	5.07
October	17.32	8.12	8.90
November	12.76	8.35	8.98
December	13.63	10.98	11.56
Average	26.18	9.46	9.98

Source: DoF, Malang, 2010

Average monthly fishery benefit is about US$ 10,000. Maximum fishery benefit generating month is February (mid of wet season) with the benefit of US$ 14,350 when reservoir storage is about 25×10^6 m^3. Such storage is about the mid level of reservoir (estimated average maximum and minimum storages in Selorejo are 12.76 and 37.9×10^6

m³). Minimum fishery benefit is observed in September (end of dry season) when storage is still in mid level. Seasonal effect as well as catching behavior might affect fish production and related benefit.

Average monthly fish production is plotted against the average monthly Selorejo storage and presented in Figure 10.4. A concave shape function is also observed (r^2 = 0.04) in this case which indicates high and low storages in Selorejo produce more fish in compare to medium storage. However, other factors (e.g. water quality, fish concentration) might affect on fish production, which has not been explored within the scope of this research. Also statistical behavior based on only three years data would be very rough.

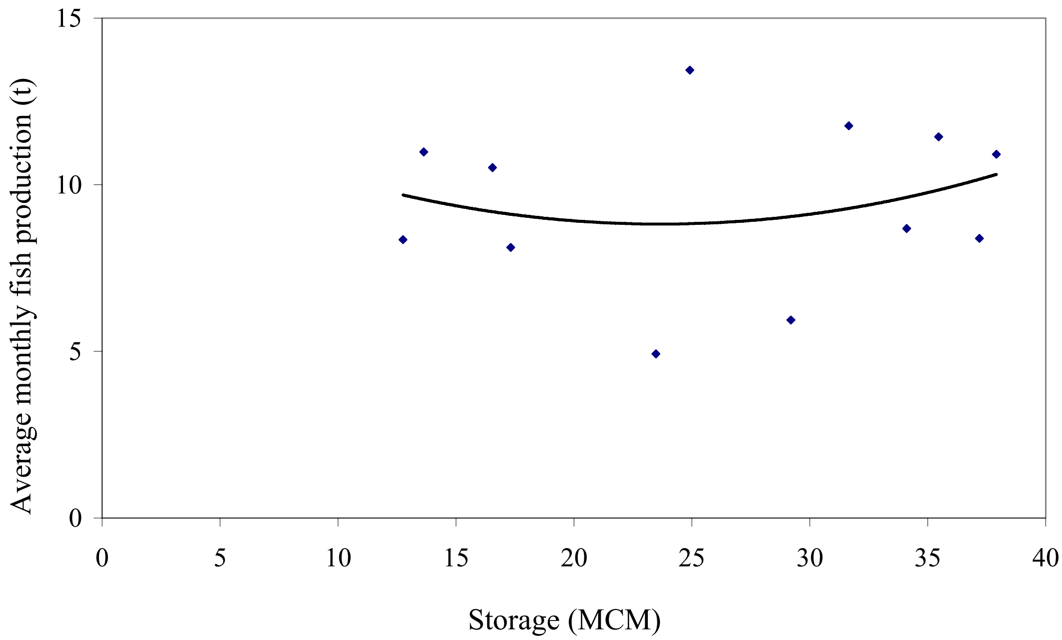

Figure 10.4 Monthly average fish production and storage of Selorejo reservoir

10.3.3 Combined benefit function for reservoir recreation and fisheries

The recreational activity and fish production and consequently related benefits are considered as a function of reservoir storage. In both cases of recreation and fishery benefit, the obtained function is a concave shape, which indicates that low and high storages generate higher benefit in compare to mid level of storage. However, the obtained functions are found very poorly fit. To have a total benefit function combining reservoir recreation and fishery and which is compatible to Aquarius, a hyperbolic tangent function is finally considered and established using Equation 3-6 based on average monthly reservoir storage and corresponding total benefit of recreational activity and fish production. The total benefit function (hyperbolic tangent function) for reservoir recreation and fishery is estimated and mentioned in Equation 10.3. Values of TB in this equation are in US$.

$$TB_{rec+fish} = 170000\left[tanh\left(0.001 * \overline{S_{j,t}} - 0.05\right) + 1\right] \qquad (10\text{-}3)$$

Where, the values of the coefficients *a, b* and *c* are 170,000; 0.001 and 0.05 respectively as Aquarius prescribed.

The actual values of benefit from reservoir recreation and fisheries with the modeled values are presented in Figure 10.5. The solid line is the linear trend line for the actual estimated benefits.

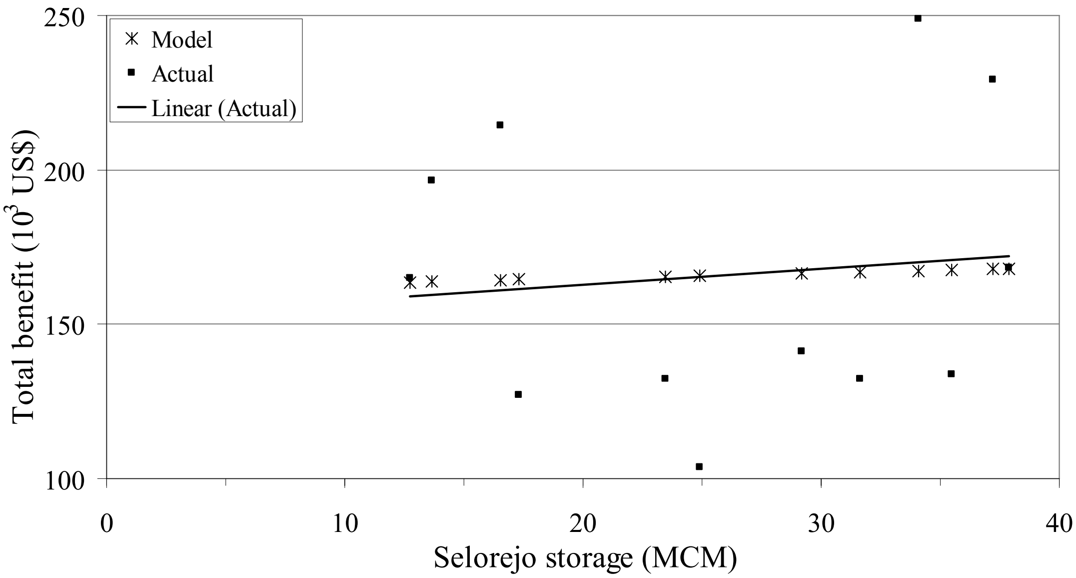

Figure 10.5 Actual and modeled total benefit from reservoir recreation and fishery

10.4 Municipal and industrial (M&I) uses

Water supply for M&I uses are quite small in amount, only 0.04 m^3/s for municipal and 0.66 m^3/s for the industrial uses. Information available on M&I uses are the average supply and average price (water service fee) per unit volume of water. Seasonal variation of demand and supply are not available in this case. Therefore, the water service fee is considered as the marginal benefit function (constant slope) for M&I uses. The M&I water service fee in Konto is IDR 84.50/m^3 (US$ 0.009/m^3) for municipal use and IDR 188.10/m^3 (US$ 0.021/m^3) for industrial uses. The weighted average of service fee of the municipal and industrial uses is US$ 0.02/m^3, which has been considered as the marginal benefit for M&I uses in the Konto.

10.5 Discussion and concluding remarks

This chapter estimates the total and marginal benefits and develops the benefit functions of the water uses (hydropower, irrigation, reservoir recreation and fisheries and municipal and industrial use) in the Konto river basin. Value of water in hydropower generation is found US$ 1.71×10^{-3}, 6.5×10^{-3} and 4.67×10^{-3} per m^3 of water passing through the turbine of Selorejo, Mendalan and Siman plants respectively. Hydropower generation depends of topography (for gaining head) and size of reservoir (for discharge). Selorejo is a small reservoir and other two plants are run-off-river types; however, the latter two have higher effective head than Selorejo plant due to topography. Moran and Dann (2008) calculated the water value for hydropower generation for Scotland using alternative cost approach and they found the value is about US$ 2.89×10^{-3} per m^3 when compare to coal generated power. On the other hand, Kadigi et al. (2008) reported the value of water in hydropower generation using power price for Tanzania and they found the value is in the range of US$ 0.06 to 0.21 per m^3.

Value of irrigation water for the Konto irrigation project appears to be US$ 0.065 per m^3 diverted and US$ 0.117 per m^3 applied water in the field whereas the figures for the TIP are US$ 0.024 and US$ 0.06 per m^3 respectively. As mentioned in Chapter 5, Hussain et al. (2007) reported the values of irrigation water from several irrigation systems in different countries and the values are in the range of US$ 0.02 to 0.07 per m^3 (details are given in section 5.4). Comparing with these values as obtained from TIP and as reported by Hussain et al. (2007), Konto irrigation project produces higher value for irrigation water use.

Value of water from reservoir recreation and fisheries is not very high in case of Selorejo. According to PJT-I officials, the Selorejo reservoir is not in fact designed for recreational purposes and also not used for fisheries. The existing fisheries are actually a subsistence activity by the local people.

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11 OPTIMAL WATER ALLOCATION IN THE KONTO RIVER BASIN

This chapter describes and estimates the optimal water allocation among the water-users in the Konto basin using hydro-economic model (HEM) and the related benefits using the benefit functions developed in Chapter 10. Background concept of HEM, model development and its applicability are already discussed in Part-I, Chapter 3 and Part-II, Chapter 8. To avoid the repetition, only empirical estimation of water allocation and related benefits for the water uses are described in this chapter.

11.1 Water allocation in the Konto River Basin using HEM

Water uses in the Konto basin is quite intriguing; water released from Selorejo reservoir is diverted to a series of power plants. Since hydropower use of water is non-consumptive, the water released from the last power-plant is used in irrigation and does not go back to the main course of Konto River. In addition, Selorejo reservoir is also used for recreational purposes and for fisheries. Small scale domestic and industrial (M&I) uses from Konto is also exist at the downstream.

11.1.1 Objective function

Maximization of economic benefit from all the water uses in the basin considering a monthly time step is carried out. Equation 11-1 is used to represent the optimization function of the water allocation. In this study, the benefit functions for the water use sectors are derived externally and then are incorporated into the optimization model.

$$\max\left(\sum_{n}\sum_{t} B_{nt} : X \in \Omega\right) \tag{11-1}$$

Where, B_{nt} is the benefit (consumer surplus) for demand node, n during time period, t and $X \in \Omega$ presents the hydrologic and economic constraints of the model. The set of constraints are considered according to Equation 3-9. Optimization problem is solved using Aquarius modeling software. Description on Aquarius is provided in section 3.4.2.

11.1.2 The Konto River Basin schematic

Four water users, namely hydropower, domestic and industrial water supply, irrigation water supply and reservoir fishery and recreation are considered for optimal water allocation in the Konto basin. Selorejo reservoir is the upstream boundary of the river network. Inflow to Selorejo acts as the model boundary. Using the water system component palette in Aquarius, the Konto river study site is assembled and presented in Figure 11.1.

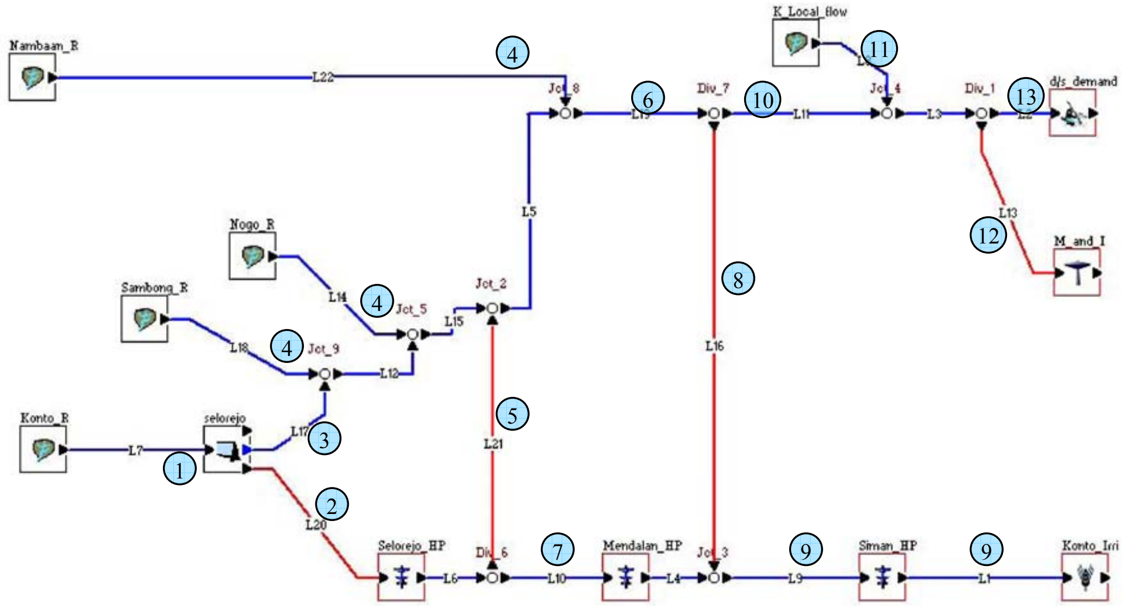

Figure 11.1 Konto River network in Aquarius modeling platform

11.1.3 Physical and economic data for 'Aquarius'

11.1.3.1 Physical data

- Inflow: inflow to the Selorejo reservoir and flow of the three tributaries, namely Sambong, Nogo and Nambaan for past 10 years (1999 – 2008) are given as input for inflow (data sets are presented in Table 9.3 and in Table F.1 of Appendix F). The local flow of Konto is also given as a separate input (dataset is reported in Table F.6 (column 5) of Appendix F).
- Reservoir: for the Selorejo reservoir following data are given as input:

  Elevation versus storage function (as a power function);
  Surface area versus storage function (as a power function);
  Initial and final storage;
  Minimum and maximum storage (based on power plant operational constraint);
  (All the above data is reported in Table H.1 in Appendix H).
- Hydropower: data related to installed capacity and design discharge for the Selorejo, Mendalan and Siman hydropower plants are given input as obtained from PJT-1. Energy rate functions are calculated and given as input. (All the input data are reported in Table H.2 in Appendix H).
- Irrigation demand site: minimum irrigation supply is considered as zero and maximum irrigation supply is taken from the monthly irrigation demand as calculated in Table 10.6. Operation constraint is treated as maximum flow, which means the diversion for irrigation would follow up to the maximum irrigation demand.
- Municipal and Industrial (M&I) demand site: Minimum supply to M&I site would be zero and the maximum supply follow the demand, which is 0.7 m^3/s for all months.

– Instream demand: minimum instream flow (equals EF) requirements at two points (as calculated in Section 9.7 and Tables 9.11 and 9.12) are considered as constraint in water allocation model. Minimum instream flow demand at Mendalan *Sabo* dam is taken as 3.22 m^3/s for the high flow season (November to April) and 1.07 m^3/s for the low flow season (May to October) to maintain a 'fair or degrading' status as defined by Tennant. Whereas, at the confluence point of Konto with Brantas, the instream demands are considered as 5.63 m^3/s for high flow season and 1.87 m^3/s for the low flow season. Water allocation is carried out for both consideration of without and with environmental flow constraints.

– Reservoir recreation and fishery: based on the analyses and function for fishery and recreation benefit in Figure 10.5, minimum and maximum storage for this purpose is considered and input as 10 and 38×10^6 m^3 respectively.

11.1.3.2 Economic data

Economic data required for optimization involves in defining the demand functions for each water use through giving input of the necessary coefficient values to specify the demand curve.

– Hydropower: constant price function is chosen for this study. US$ 21.76 per MWh is the rate here, which corresponds to IDR 196.69 per kWh.

– Irrigation: two options are available in defining irrigation water use demand function, namely: exponential decaying price and constant price. However, the established demand function (or marginal benefit function, as shown in Figure 10.2) is linear The linear demand curve is converted into a fitted exponential curve (as discussed and shown in Appendix H, Table H.3 and Figure H.5) and the parameter values are used in the model. The values of the parameters *a* and *b* for the exponential function ($y=ae^{-x/b}$) are respectively 78900 and 265 and given as input;

– Reservoir recreation and fishery: based on the benefit function as developed earlier in Equation 10-3, the parameter values are given as input to the Aquarius model. Parameters a, b, and c values are respectively 170,000; 0.001 and 0.05.

– M&I uses: a constant price function is considered for this study. Weighted average value of municipal and industrial water service fee is calculated, which is US$ 0.02 per m^3 (IDR 182.20/m3) and this number is given as the input for demand function of M&I uses.

11.1.4 Verification of the water allocation model

Inflow to Selorejo reservoir is known and acts as the upper boundary of the model. Reservoir operation is constrained on minimum and maximum storage. Based on this boundary and constraints, the model is set up in Aquarius and run with six years (2003 - 2008) mean monthly dataset to maximize overall basin benefit. Six years data is used because only in this period all the users are in operation. Downstream of Selorejo, only observed information is the Selorejo release and observed power productions, which are compared with the Aquarius output. The model output of Selorejo release fits with the observed release data with an r^2 value of 0.79 (Figure 11.2), which is considered to be a satisfactory fit. Difference in observed and modeled released data is might be due to not having a well fitted power relation between elevation versus storage and area versus storage for Selorejo (as shown in Figures H.1 and H.2 in Appendix H); however, Aquarius deals only with power relation.

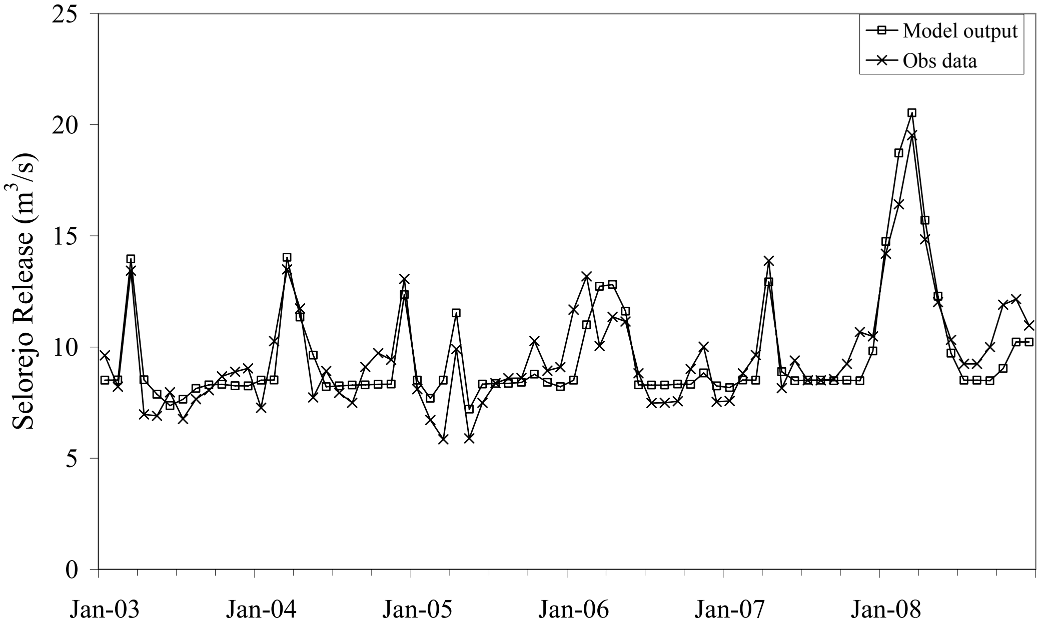

Figure 11.2 Comparison between model output and observed Selorejo release

11.2 Results – optimization model

The optimization model is first run for the existing operation policy, which refers to maximization of economic benefit without any constraint. Minimum and maximum storage for the Selorejo and maximum discharge capacity to the power plants are the operational constraints (maximum diversion) used. This scenario is termed as the baseline scenario (S0, Case-I). Several other alternative scenarios (as tabulated in Table 11.1) are also run and the sensitivity of the model is carried out.

Table 11.1 Scenarios considered for optimal water allocation in Konto river basin

Scenario	Description
S0	Baseline (existing operation policy)
S1	Dry year flow (25% lower flow than the average year flow)
S2	Wet year flow (25% higher flow than the average year flow)
S3	Maintaining high water level (620 m) in the Selorejo reservoir to facilitate reservoir recreation and fishery
S4	Maintaining low water level (610 m) in the Selorejo reservoir to observe the loss from reservoir recreation and fishery
S5	Low level of EF
S6	High level of EF

For each individual scenario including the baseline, two cases are considered, namely; Case-I: benefit maximization (without EF constraint meaning that water is allocated to maximize overall benefit) and Case-II: environmental protection by ensuring environmental flow requirements at Mendalan *Sabo* dam point.

In the above mentioned scenarios of S0 to S4, Case-II is run with an EF level of 'fair or degrading' status as defined by Tennant. However, another two other alternative cases are also considered one with one step lower than the 'fair' level and another with higher than the 'fair' level of EF. In case of lower level of EF (Scenario 5), a 'poor' condition for the high flow season (with a flow of 1.07 m^3/s at Mendalan *Sabo* dam and 1.87 m^3/s for most downstream point) and 'severe degradation' for the low flow season (with a flow of 0.75 m^3/s at Mendalan *Sabo* dam and 1.50 m^3/s for the confluence point with Brantas) is considered (Tables 9.11 and 9.12). In case of a higher level of EF (Scenario 6), 'good' environmental status is considered, which corresponds flow of 4.3 and 2.15 m^3/s for high and low flow season respectively at Mendalan *Sabo* dam (Table 9.11) and 7.51 and 3.75 m^3/s of flow for high and low flow season respectively at the most downstream point (at confluence with Brantas) (Table 9.12). Scenarios 5 and 6 are run with an average flow year condition.

11.2.1 Baseline optimal solution

The baseline scenario is run with mean monthly inflows for six years (2003 – 2008) to the Selorejo reservoir without any restriction in water allocation, which implies an allocation of water to maximize economic benefit. Six years data is used because the Mendalan and Siman power plants came into operation since 2003 meaning that all the water-users came into operation from 2003. Diversion of Selorejo water to hydropower plants to maximize the power production is fully utilized here. Table 11.2 presents the monthly water allocation to the water users as well as the flow balance for the river system for high and low flow season. It is evident from Table 11.2 that current operation of the system does not satisfy EF at Mendalan *Sabo* dam point whereas at the most downstream point EF is satisfied due to local flow and no major abstraction of river water after Mendalan *Sabo* dam. The estimated flow and environmental flow requirements at Mendalan *Sabo* point for the entire analysis period are shown in Figure 11.3. The figure depicts that particularly in dry season the river becomes almost dry with zero flow.

The baseline scenario, therefore, is again run with the constraint of minimum EF requirements at the Mendalan *Sabo* dam point as well as at the most downstream point. The EF values are already mentioned earlier. 'Fair or degrading' condition is considered for all scenarios except Scenarios 5 and 6. This run is terms as Scenario 0, Case-II and for this run, the water allocation and flow balances are checked and presented in Table 11.3.

Table 11.2 Monthly water allocation and flow balance at the Konto study site without EF constraints (Scenario S0, Case-I) (Unit: m^3/s)

Month	Inflow to SR	SR release to SHP	Flow in Konto d/s SR	Flows Sambong Nogo, & Nambaan	Return flow from SHP	Flow above Mndln *Sabo* dam	Flow to MHP	Supply to Siman DRP	Flow to Siman HP=irr supply	D/S of Mndln *Sabo* Dam	Local flow of Konto	Supply to M&I	Konto flow before meeting to Brantas
	1	2	3	4	5	6	7	8	9	10	11	12	13
High flow (wet) season													
Nov	8.61	8.42	0.00	0.28	0.00	0.28	8.42	0.08	8.50	0.20	10.70	0.70	10.20
Dec	10.95	8.38	0.00	0.34	0.00	0.34	8.38	0.12	8.50	0.22	10.38	0.70	9.90
Jan	11.62	8.61	0.00	0.47	0.11	0.58	8.50	0.00	8.50	0.58	9.72	0.70	9.60
Feb	16.75	13.47	0.00	0.66	4.97	5.63	8.50	0.00	8.50	5.63	6.27	0.70	11.20
Mar	15.44	14.78	0.00	0.63	6.28	6.91	8.50	0.00	8.50	6.91	5.59	0.70	11.80
Apr	13.11	13.33	0.00	0.49	4.83	5.32	8.50	0.00	8.50	5.32	7.43	0.70	12.05
Average	12.75	11.17	0.00	0.48	2.70	3.18	8.47	0.03	8.50	3.14	8.35	0.70	10.79
Low flow (dry season)													
May	10.39	10.27	0.00	0.39	1.77	2.16	8.50	0.00	8.50	2.16	8.59	0.70	10.05
Jun	8.41	8.63	0.00	0.35	0.13	0.48	8.50	0.00	8.50	0.48	9.52	0.70	9.30
July	7.26	8.51	0.00	0.30	0.01	0.31	8.50	0.00	8.50	0.31	8.69	0.70	8.30
Aug	6.55	8.35	0.00	0.27	0.00	0.27	8.35	0.15	8.50	0.12	8.68	0.70	8.10
Sep	6.54	8.36	0.00	0.25	0.00	0.25	8.36	0.14	8.50	0.11	9.29	0.70	8.70
Oct	7.27	8.35	0.00	0.25	0.00	0.25	8.35	0.15	8.50	0.10	10.6	0.70	10.00
Average	7.74	8.75	0.00	0.30	0.32	0.62	8.43	0.07	8.50	0.55	9.23	0.70	9.08

Note: SR = Selorejo reservoir; SHP = Selorejo hydropower plant; MHP = Mendalan hydropower plant; DRP = daily retention pond; Column numbers are the locations as shown in Figure 11.1

Table 11.3 Monthly water allocation and flow balance at the Konto study site with EF constraints (Scenario S0, Case-II) (Unit: m^3/s)

Month	Inflow to SR	SR release to SHP	Flow in Konto d/s SR	Flows Sambong Nogo, & Nambaan	Return flow from SHP	Flow above Mndln *Sabo* dam	Flow to MHP	Supply to Siman DRP	Flow to Siman HP=irr supply	D/S of Mndln *Sabo* Dam	Local flow of Konto	Supply to M&I	Flow before meeting to Brantas
	1	2	3	4	5	6	7	8	9	10	11	12	13
High flow (wet) season													
Nov	8.61	5.20	3.22	0.28	0.00	3.50	5.20	0.28	5.48	3.22	10.70	0.70	13.22
Dec	10.95	5.16	3.22	0.34	0.00	3.56	5.16	0.34	5.50	3.22	10.38	0.70	12.90
Jan	11.62	5.39	3.22	0.47	0.00	3.69	5.39	0.47	5.86	3.22	9.72	0.70	12.24
Feb	16.75	10.25	3.22	0.66	1.75	5.63	8.50	0.00	8.50	5.63	6.27	0.70	11.20
Mar	15.44	11.56	3.22	0.63	3.06	6.91	8.50	0.00	8.50	6.91	5.59	0.70	11.80
Apr	13.11	10.11	3.22	0.49	1.61	5.32	8.50	0.00	8.50	5.32	7.43	0.70	12.05
Average	12.75	7.95	3.22	0.48	1.07	4.77	6.88	0.18	7.06	4.59	8.35	0.70	12.24
Low flow (dry) season													
May	10.39	9.20	1.07	0.39	0.70	2.16	8.50	0.00	8.50	2.16	8.59	0.70	10.05
Jun	8.41	7.56	1.07	0.35	0.00	1.42	7.56	0.35	7.91	1.07	9.52	0.70	9.89
July	7.26	7.44	1.07	0.30	0.00	1.37	7.44	0.30	7.74	1.07	8.69	0.70	9.06
Aug	6.55	7.28	1.07	0.27	0.00	1.34	7.28	0.27	7.55	1.07	8.68	0.70	9.05
Sep	6.54	7.29	1.07	0.25	0.00	1.32	7.29	0.25	7.54	1.07	9.29	0.70	9.66
Oct	7.27	7.28	1.07	0.25	0.00	1.32	7.28	0.25	7.53	1.07	10.6	0.70	10.97
Average	7.74	7.68	1.07	0.30	0.12	1.49	7.56	0.24	7.80	1.25	9.23	0.70	9.78

Note: SR = Selorejo reservoir; SHP = Selorejo hydropower plant; MHP = Mendalan hydropower plant; DRP = daily retention pond; Column numbers are the locations as shown in Figure 11.1

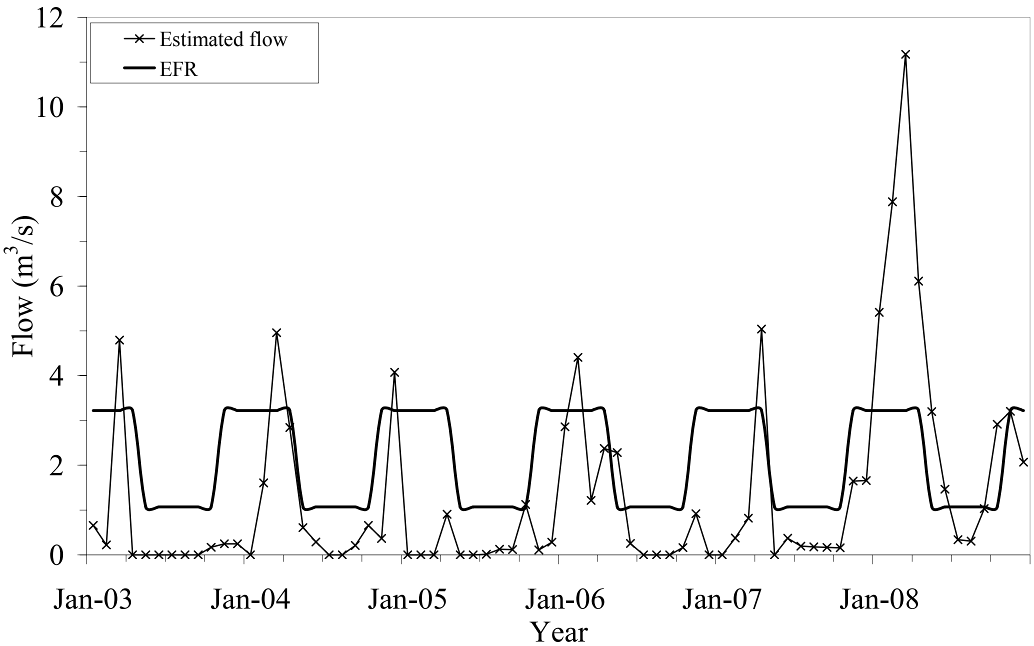

Figure 11.3 Estimated flow and environmental flow requirements at Mendalan *Sabo* dam

Total 308×10^6 m^3 of water passes through the Selorejo power plant turbine that produces 25,951 MWh energy annually with a value of US$ 0.567 million (IDR 5,106 million) (Table 11.4). From this 308×10^6 m^3 of water, 45×10^6 m^3 water is again diverted back to Konto and remaining 263×10^6 m^3 of water is being used by Mendalan power plant that produces 78,844 MWh energy with the value of US$ 1.722 million (IDR 15,506 million) in annual basis. Again 5×10^6 $m^3$of water is diverted to Siman power plant from Mendalan *Sabo* dam point. Total 268×10^6 m^3water is used in Siman power plant where 57,611 MWh energy is produced with a value of US$ 1.258 million (IDR 11,328 million). Cumulative benefit from power generation by water at this point is US$ 3.547 million (IDR 31,940 million). From the released water of Siman power plant, 157×10^6 m^3water is used in Konto irrigation project based on monthly demand of irrigation. However, irrigation benefit is higher than power production benefit. Irrigation benefit in this scenario is US$ 10.219 million (IDR 92,018 million). Benefit from reservoir recreation and fishery in this scenario is US$ 2.080 million (IDR 18,730 million) and M&I uses is US$ 0.435 million. Total basin benefit in this scenario without considering EF (S0, Case-I) is US$ 16.282 million (IDR 146,610 million).

The baseline scenario is also run with the constraint of satisfying the minimum EF requirements downstream to Mendalan *Sabo* dam. Ensuring river health through provisioning EF causes a net benefit reduction of US$ 1.067 million (IDR 9,608 million) that comprises US$ 0.558 million reduction from power production and US$ 0.509 million from irrigation sector. Table 11.4 represents sectoral water use and benefits for this scenario and for both the cases.

Table 11.4 Water supply and related benefits from all water uses for Konto study site in baseline scenario

Water user	Water supply (10^6 m^3/yr)	Energy generation (MWh/yr)	Benefit/unit vol of water (US\$/10^3 m^3)	Total benefit (10^6 US\$/yr)	Cumulative Benefit (10^6 US\$/yr)
	Case I: Without consideration of Environmental flow requirements				
Selorejo HP	308	25,951	1.841	0.567	0.567
Mendalan HP	263	78,844	6.541	1.722	2.289
Siman HP	268	57,611	4.694	1.258	3.547
Total HP		162,406	13.076	3.547	
Irrigation	157		65.020	10.219	13.766
M&I	21.8		20.000	0.435	14.201
RRF	31.5		65.908	2.080	16.281
	Case II: With consideration of Environmental flow requirements				
Selorejo HP	245	20,653	1.847	0.444	0.444
Mendalan HP	227	68,109	6.544	1.463	1.908
Siman HP	235	50,538	4.697	1.081	2.989
Total HP		139,300	13.088	2.989	
Irrigation	139		71.781	9.710	12.699
M&I	21.8		20.000	0.435	13.134
RRF	31.5		65.908	2.080	15.214

Note: RRF = Reservoir Recreation and Fishery

11.2.2 Alternative runs – sensitivity analysis

The optimization model is run for all the above mentioned scenarios (S0 – S6) with both Cases I and II. Optimal allocation of water between the sectors for the scenarios considered are estimated and presented in Table 11.5. Maintaining EF at the downstream (Case-II) results less allocated water compare to non-maintaining EF (Case-I) to all users except M&I uses at the downstream part of the basin for all the scenarios considered. EF requirements at the most downstream point of Konto are mostly met by local flow, therefore, EF requirements at Mendalan *Sabo* dam point controls the allocation for the Case-II analysis. The highest amount of water is used by the Selorejo power plant followed by Siman and Mendalan plants, irrigation, reservoir recreation and M&I use.

The power production variations across the scenarios analyzed are examined. Table 11.6 presents the power production from each hydropower plant and for all scenarios and cases analyzed; the table also shows the change in power production for each scenario and case with respect to the baseline scenario (S0, Case-I). Ensuring EF causes a decrease in power production for all the scenarios, whereas increased flow level results higher production.

Table 11.5 Optimal water allocations to different sectors in different scenarios

Scenario	Case	Optimal water allocation to user (10^6 m^3)			
		Hydropower and Irrigation		M&I	RRF
S0	I	308*	(MHP = 308 – 45 = 263, SHP = 263 + 5 = 268, Irr = 268 – 111 = 157)$^{\Omega}$	21.8	31.5
	II	241	(MHP = 241 – 17 = 224, SHP = 224 + 6 = 230, Irr = 230 – 95 = 135)	21.8	31.5
S1	I	252	(MHP = 252 – 3 = 249, SHP = 249 + 5 = 254, Irr = 254 – 111 = 143)	21.8	25.8
	II	185	(MHP = 185 – 0 = 185, SHP = 185 + 9 = 194, Irr = 194 – 77 = 117)	21.8	25.8
S2	I	370	(MHP = 370 – 102 = 268, SHP = 268 + 0=268, Irr = 268 – 111 = 157)	21.8	34.8
	II	315	(MHP = 315 – 61 = 254, SHP = 254 + 5 = 259, Irr = 259 – 111 = 148)	21.8	34.8
S3	I	301	(MHP = 301 – 56 = 245, SHP = 245 + 5 = 250, Irr = 250 – 107 = 143)	21.8	33.0
	II	241	(MHP = 241 – 28 = 213, SHP = 213 + 6 = 219, Irr = 219 – 97 = 122)	21.8	33.0
S4	I	323	(MHP = 323 – 72 = 251, SHP = 251 + 3 = 254, Irr = 254 – 111 = 143)	21.8	11.7
	II	262	(MHP = 262 – 35 = 227, SHP = 227 + 5 = 232, Irr = 232 – 110 = 122)	21.8	11.7
S5	II	279	(MHP = 279 – 34 = 245, SHP = 245 + 5 = 250, Irr = 250 – 106 = 144)	21.8	31.5
S6	II	206	(MHP = 206 – 7 = 199, SHP = 199 + 10= 209, Irr = 209 – 90 = 119)	21.8	31.5

Note: Scenarios and cases are as defined earlier; * water allocated to first power plant, Selorejo; $^{\Omega}$ distribution of water which is released from Selorejo, number with –ve sign indicates flow going out of the system and vice versa, MHP is Mendalan power plant, SHP is Siman power plant; RRF = average Selorejo storage for recreation and fishery

Variation in power production is higher for the Selorejo plant (55 – 122%) than the other two plants (70 – 102% for Mendalan and 72 – 100% for Siman plant). The lowest power production is observed in dry year scenario when inflow to Selorejo is less and the opposite case happens in wet year scenario. Variation in Mendalan and Siman plants are less because of their run-off-river type nature, their production varies only with flow, however, Selorejo production varies with flow and water level in Selorejo reservoir. Maintaining low water level at Selorejo also results low power production from Selorejo plant due to low effective head. Overall power production varies within the range of 69 – 105% across the scenarios and cases analyzed.

For the agricultural practices in Konto, Dry-2 (Jul - Oct) is the driest part in the year and in this time *Palawija* (Dry-2) is the main crop. These crops shares almost 70% of all the irrigation water. The change in yield of *Palawija* (Dry-2) is analyzed for each scenario considered and presented in Figure 11.4. The yield is observed reaching maximum in baseline (S0, Case-I) as well as in Wet year Scenario (Case-I). Ensuring EF at downstream results less flow diversion to power plants and subsequently less water to irrigation project which results decreased yield of the crop. Highest loss in yield is observed while keeping

Selorejo water level to a fixed position and ensuring EF simultaneously (Scenarios S3 & S4, Case-II).

Table 11.6 Energy production (MWh) and its variation for different scenarios analyzed

Scenario	Case	Hydropower plant			Total energy production
		Selorejo	Mendalan	Siman	
S0	I	25,951	78,844	57,611	162,407
	II	20,344 (78)	66,987 (85)	49,511 (86)	136,843 (84)
S1	I	19,413 (75)	74,554 (95)	54,541 (95)	148,508 (91)
	II	14,362 (55)	55,391 (70)	41,740 (72)	111,494 (69)
S2	I	31,694 (122)	80,257(102)	57,612 (100)	169,562(104)
	II	26,971 (104)	76,181 (97)	55,640 (97)	158,791 (98)
S3	I	25,570 (99)	73,299 (93)	53,540 (93)	152,409 (94)
	II	20,401 (79)	63,476 (81)	46,991 (82)	130,868 (81)
S4	I	20,174 (78)	74,926 (95)	54,439 (94)	149,538 (92)
	II	16,365 (63)	67,679 (86)	49,738 (86)	133,782 (82)
S5	II	23,556 (91)	73,354 (93)	53,723 (93)	150,633 (93)
S6	II	16,868 (65)	58,818 (75)	44,360 (77)	120,046 (74)

Note: value in parenthesis is % energy production with respect to production of S0, Case-I

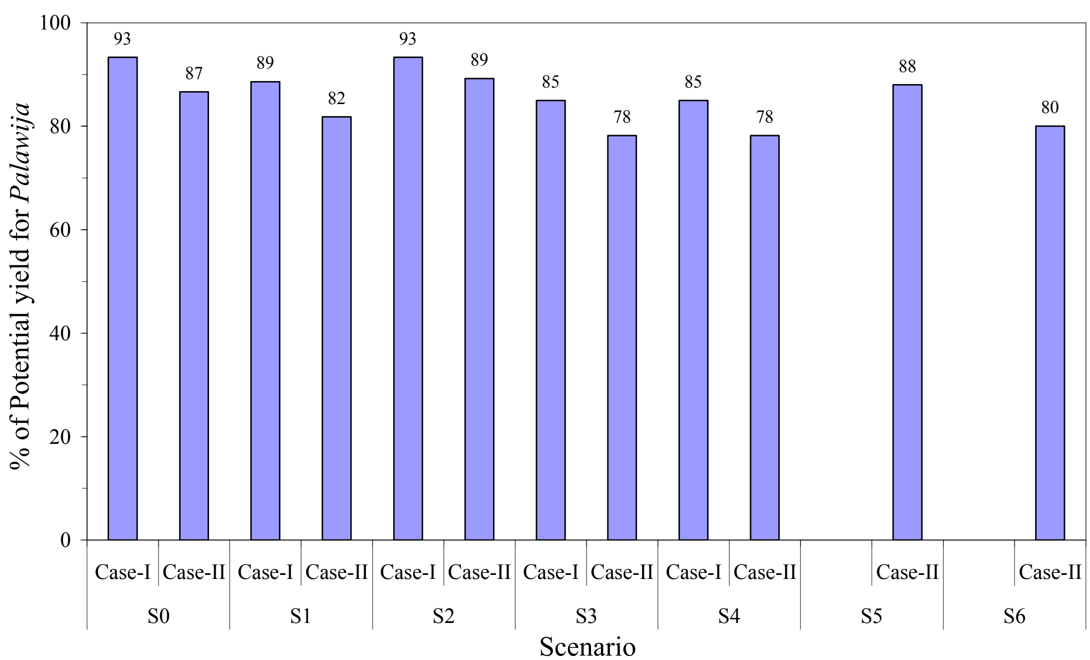

Figure 11.4 Ratio of actual to potential yield of *Palawija* (Dry-2) in different scenarios and cases analyzed

Benefits from each water-using sector for all the scenarios and cases considered are estimated and presented in Table 11.7. It is evident from the analysis that the baseline scenario or the existing operation policy is probably the most efficient setup in terms of achieving water use benefits in economic terms at the basin scale. Higher the inflow (wet year scenario, S2) still generates higher benefit than average flow year, which indicates that there is shortage of flow in average flow year. Ensuring EF results benefit reduction from existing water uses since the users receive less water and water goes for river maintenance; however, benefits from direct or indirect use of instream flow has not been revealed here. Maintaining certain water level in Selorejo does not affect much on reservoir related benefits rather it causes reduction in power production and overall benefits. Highest benefit generating water-use is again the irrigation in this basin; however, due to cascading use of the same water, value of unit volume of water increases considerably along its use path of hydropower followed by irrigation; which might result conflict between the current water use practice and provisioning of environmental flows.

Table 11.7 Benefits (10^6 US$) from water uses for the Konto study site in different scenarios analyzed

Scenario	Case	Benefit (10^6 US$) from water-use sector						Total basin benefit
		Hydropower			Irrigation	RRF	M&I	
		Selorejo	Mendalan	Siman				
S0	I	0.567	1.722	1.258	10.219	2.080	0.435	16.281
	II	0.444	1.463	1.081	9.710	2.080	0.435	15.214
S1	I	0.424	1.628	1.191	9.418	2.068	0.435	15.164
	II	0.314	1.210	0.912	8.553	2.068	0.435	13.492
S2	I	0.692	1.753	1.258	10.219	2.086	0.435	16.443
	II	0.589	1.664	1.215	9.992	2.086	0.435	15.981
S3	I	0.559	1.601	1.169	9.687	2.083	0.435	15.534
	II	0.446	1.386	1.026	9.174	2.083	0.435	14.550
S4	I	0.441	1.637	1.189	9.687	2.039	0.435	15.428
	II	0.357	1.478	1.086	9.174	2.039	0.435	14.569
S5	II	0.515	1.602	1.173	9.834	2.080	0.435	15.639
S6	II	0.382	1.302	0.980	9.142	2.080	0.435	14.321

Note: RRF = reservoir recreation and fishery; Scenarios and cases are as described in the text

Sectoral water use benefits with respect to benefit received from the same sector in the baseline scenario (S0, Case-I, i.e. maximum possible benefit without considering environmental water requirements) is plotted and presented in Figure 11.5, which provides insight into the sensitivity of the model and scenario that affects on achieving benefit from a particular sector. Hydropower benefit is observed the most sensitive for any change in operation policy and particularly it is due to Selorejo power plant, whose benefit depends on two factors, namely Selorejo release and its water level simultaneously. For other two hydropower plants, power generation depends only on flow since they are run-off-river type. Benefit from reservoir recreation and fishery is observed as the least sensitive to any scenario analyzed. It is due to the developed benefit function for reservoir recreation and fishery (Equation 10-3), which is almost a flat line and does not vary considerably with Selorejo storage but in actual cases the benefits are found in a concave shape with reservoir storage. However, Aquarius only deals with hyperbolic tangent function as developed in Equation 10-3. Irrigation sector depends on power plants flow and its benefit also varies with almost similar manner like in power production benefit. M&I uses always receive water according to the demand and the benefit from this sector does not have any change across the scenarios and cases.

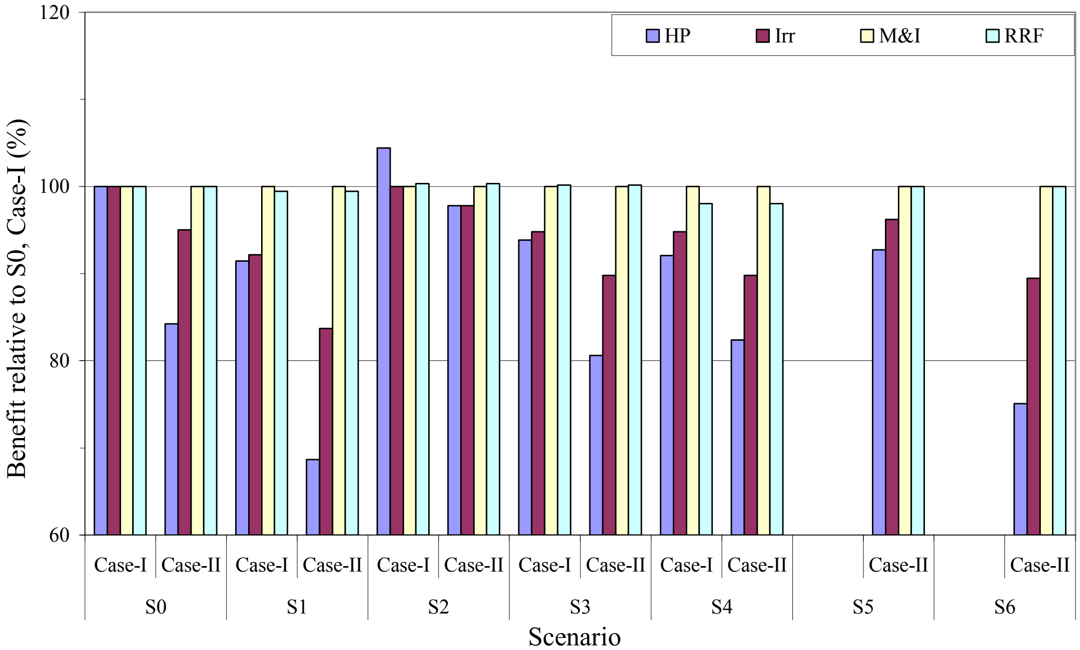

Figure 11.5 Sensitivity of sectoral benefits of water uses from different scenarios analyzed

11.2.3 Basin benefits at different EF levels

Since ensuring EF results decrease in flow to the power plants followed by irrigation project and subsequent reduction in economic benefit from the basin, three levels of EF is evaluated to realize the variation in overall benefit, which will eventually help the basin managers to take decision in adopting EF for the basin. Three EF levels are namely; 'poor (high flow season)-to-severe (low flow season)', 'fair' and 'good' status as define by Tennant. For the three levels EF requirements at Mendalan *Sabo* dam are 1.07, 3.22 and 4.3 m^3/s for the high flow season (November – April) and 0.75, 1.07 and 2.15 m^3/s for the low flow season (May – October) respectively; similarly the EF requirements at the most downstream point of Konto (above its confluence with Brantas) are 1.87, 5.63 and 7.51 m^3/s for high flow season and 1.5, 1.87 and 3.75 m^3/s for low flow season respectively for three levels of EF.

Analysis shows that, increase in EF level directly affects in negative direction on the basin overall benefit particularly when only the direct offstream water use benefits are accounted. For the 'poor to severe', 'fair or degrading' and 'good' levels of EF provisioning, the overall benefits are respectively US$ 15.638, 15.214 and 14.321 million as shown in Figure 11.6. Increase in EF level by one step (as defined by Tennant) results 6% reduction in economic benefit, whereas decrease in EF level by one step increase the economic benefit by 3%. Such analysis provides insight into the cost of EF provisioning in the basin. In this benefit estimation, only direct water uses are considered and in Konto basin no major direct instream water (EF) use is observed or documented to the water management authorities. Accounting the benefits of environmental and indirect use of EF is beyond the scope of this study. Including all benefits in the allocation model might change the optimal allocation pattern and overall benefit.

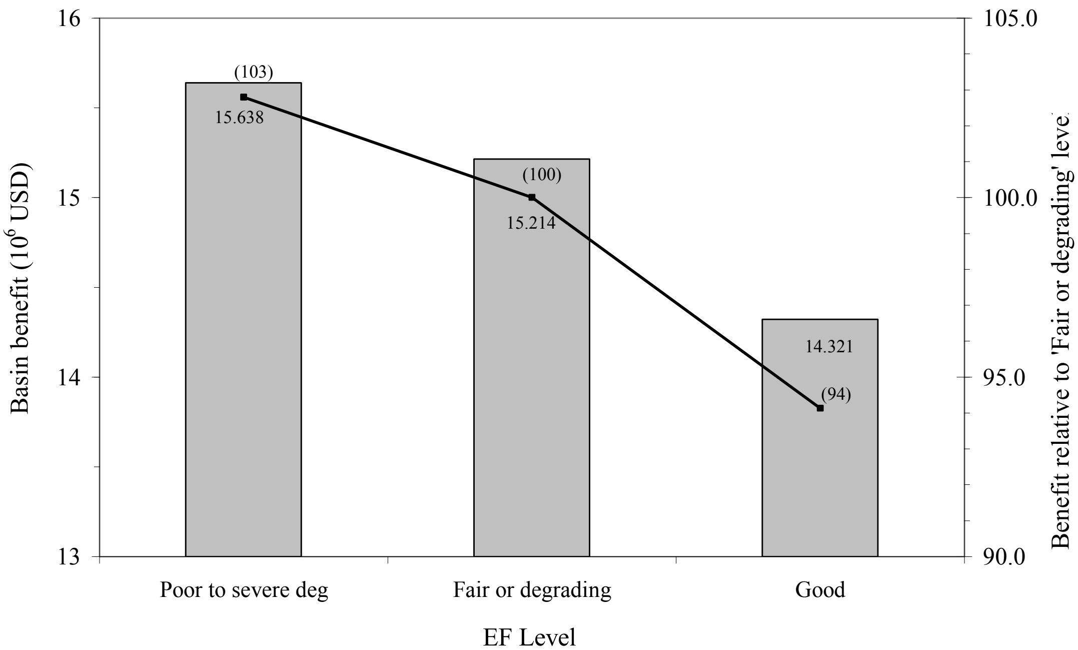

Figure 11.6 Change in basin benefit due to different level of EF provisioning

11.2.4 Tradeoff analysis

Without and with consideration of monthly environmental water demands, total benefits for different scenarios are analyzed and the tradeoff for maintaining EF is found out by comparing the benefit garnered from baseline scenario (S0, Case-I). Table 11.8 presents the basin wide benefit for both the cases of EF consideration and not EF consideration. Figure 11.7 depicts the tradeoff situation between benefit maximization and environmental protection from the Konto river basin for different scenarios analyzed.

Table 11.8 Summary results of overall water use benefits for alternative scenario analysis for Konto

Scenario	**Basin benefit (10^6 US$)**	
	Without consideration of EF (case-I)	**With consideration of EF (case-II)**
Baseline (S0)	16.281	15.214
S1 (dry year)	15.165	13.491
S2 (wet year)	16.444	15.982
S3 (Selorejo WL 620 m)	15.534	14.550
S4 (Selorejo WL 610 m)	15.428	14.570
S5 (‘Poor’ EF level)	---	15.638
S6 (‘Good’ EF level)	---	14.321

Scenarios and case as defined in the text

Maintaining environmental flow reduces the total economic benefit in each scenario analyzed as depicted in Figure 11.7. In case of dry year and ‘good’ EF level the difference is the maximum whereas in wet year the difference becomes low since flow increases in wet year. This indicates that inflow to the reservoir is the controlling factor/variable to the overall benefit.

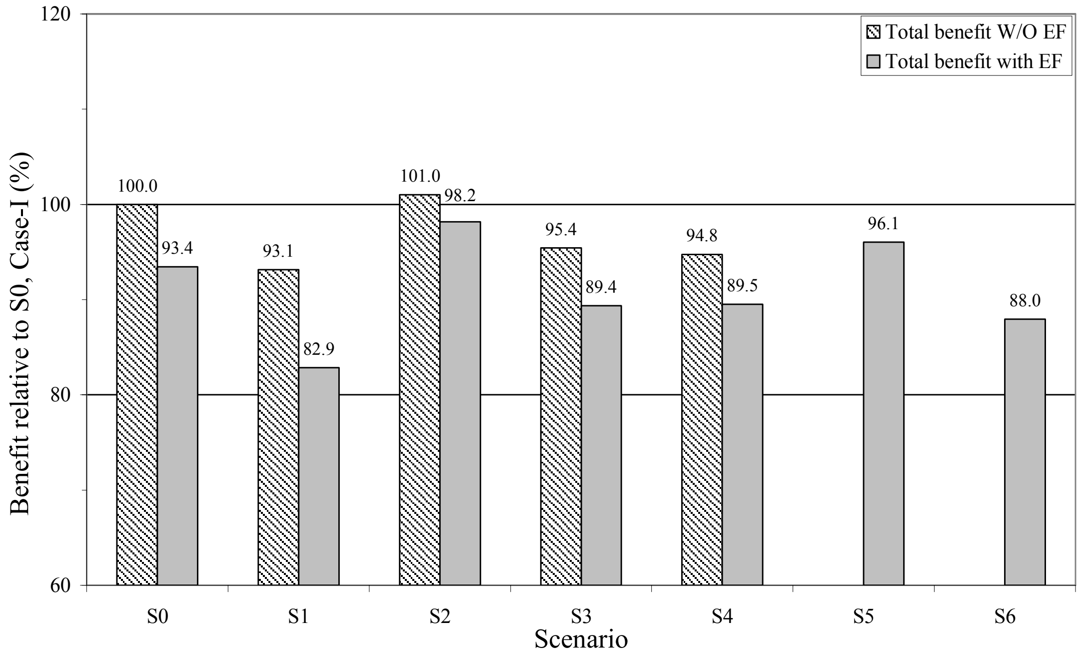

Figure 11.7 Tradeoff between benefit maximization and environmental protection for the Konto basin in different scenarios analyzed

11.3 Concluding remarks

The outcomes of the analyses clearly show the power production, sectoral and overall benefits in different scenarios and cases considered. Existing operation policy predominantly focuses on maximization of power production and does not satisfy EF requirements at Mendalan *Sabo* dam point which is about ten kilometers downstream of Selorejo reservoir. Environmental flow is met at the most downstream part of Konto since there is no major abstraction of water from the river, but a local flow is observed. Maintaining EF for the entire river results reduction in overall economic benefit. However, the optimal water allocation and related benefits as estimated in this chapter will help water management authorities in realizing the tradeoff between power productions, benefit maximization and maintaining EF. The benefit from reservoir recreation and fisheries are small and Selorejo water level does not influence much on the benefit of this sector. Maintaining certain water level to facilitate reservoir recreation and fishery will not be efficient in terms of overall benefit maximization. However, at least lower level of EF (as analyzed in this chapter) at Mendalan *Sabo* dam point is strongly recommended to maintain river health and environmental protection of the river and aquatic ecosystem there.

Stern data paucity was the biggest challenge for this study. No data and information was found on instream water uses (direct or indirect use). Environmental flow is only estimated by Tennant method since other methods (FDC or RVA) need daily flow data for at 20 years. Reservoir recreation and fishery data was only for eight and three years respectively, which is not enough for any statistical analysis. Building up strong database is also recommended for accurate analysis and efficient management of the water resources for the Konto river basin.

Das Gupta (2008) mentioned that since withdrawals of water increase, many river basins will face the challenge of maintaining the critical levels of environmental flows in near future. The process is unlikely to be reversed until environmental flow allocation is integrated into river basin management plan. Analyses and results in this chapter carries importance in providing insight into economic loss and gain of ensuring EF for the river, which will facilitate in integrating EF into water management plan of the river. Finally, the analyzed results provide a reasonable starting point for reconciling the competing needs of the environmental and other water uses and will act as a basis for informed policy decision and adopting environmentally sound water management particularly for the Konto river basin.

PART-IV

Chapter 12: Summary, conclusions and recommendations

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12 SUMMARY, CONCLUSIONS AND RECOMMENDATIONS

12.1 Summary

Water requirements for the environment or for the river itself are becoming vital in basin water resources management in particular for water allocation process. Efficient water allocation requires information on water use value in different uses; however, daunting challenge of accurate valuation of water for both off- and in-stream uses often lies. A water-use is considered offstream when water is extracted from the river for consumptive use such as municipal and industrial use or agricultural use. Conversely, instream uses refer to non-consumptive water uses that take place onto the river stream itself, examples include fisheries, navigation etc. In many cases, instream uses – often indirect or small scale subsistence uses – are ill-documented and bear small economic value as compared to offstream uses, but carry considerable social and environmental importance. Analyzing the tradeoff between the sectors is essential whilst management constantly seeks to maximize the benefit from the limited resource. To support an economic efficiency orientation to this crucial issue of water allocation, the doctoral research, reported in this dissertation, undertook to establish the total and marginal benefit functions for off- and in-stream water uses in the case study rivers, to assess the environmental water requirements and to formulate an optimal water allocation model that elucidates sectoral and overall benefits as well as the tradeoff between benefit maximization and environmental protection. The Teesta River from Bangladesh and the Konto River from East Java Island of Indonesia are taken as case study sites.

Teesta is the forth main river in terms of flow in Bangladesh; it supplies water to the largest irrigation project in Bangladesh through the Teesta barrage. The river exhibits high seasonal flow variability and causes inundation of floodplains in monsoon and extremely low flow conditions in dry seasons. Largely ignoring the in-stream flow requirements, river flow is diverted to irrigation resulting in severe low flow condition downstream to the barrage, which critically affects the in-stream flow direct-uses, namely capture fisheries and small scale navigation. On the other hand, Konto is a tributary and sub-basin of Brantas river system in East Java, Indonesia. Total basin area of Konto is 687 km^2. River flow is regulated through Selorejo reservoir which was commissioned on 1970. A cascading series of three successive hydropower plants that use the same water is the main feature of this basin. Water released from the most downstream power plant is further used for irrigation. The reservoir system is operated to obtain maximum possible hydropower production without due consideration to river maintenance flow at the downstream. Hydropower generation, irrigation, reservoir recreation and fisheries and small scale municipal and industrial supplies are the main water uses in the Konto river basin.

The research comprises two interlaced subject matters – developing benefit functions for all the off- and in-stream water direct uses in a river basin and setting up a model that considers temporal and spatial allocation of water among all the users to maximize overall benefit. Several tools and analysis techniques are used in developing the benefit functions for the water uses, whereas ‘Aquarius’ modeling platform is used for optimization.

Monthly environmental water demands are assessed separately and treated as constraints to the optimization model.

For both the case study sites, irrigation water requirements for the crops and the aggregated demand at the project level are estimated using field water balance approach for the lowland rice and CROPWAT model for the other upland crops. Residual imputation method is employed to calculate the value of irrigation water. The average value of diverted irrigation water is estimated US$ 0.024 and 0.065 per cubic meter for the case of Teesta and Konto respectively. Water-crop production-function estimating the crop yield in relation with varying level of assumed water-shortage forms the basis towards establishing the total and marginal benefit function for irrigation water with the underlying consideration that the non-water inputs in the production process would be same for all the water-shortage cases. Total benefit function is considered to be a quadratic function that results in a linear downward slope marginal benefit function. Analysis showed that an average monthly flow of 136 m^3/s can meet the full irrigation demand for TIP and generates the maximum total benefit of US$ 49.6 million and the marginal benefit of about US$ 0.36 million per m^3/s of diverted flow. Marginal benefit would become US$ 0.48 million per m^3/s when the flow decreased to half i.e. 68 m^3/s. In case of Konto, an average monthly flow of 16.5 m^3/s is required to satisfy irrigation demand. If full supply is ensured irrigation water benefit reaches US$ 16.62 millions, which corresponds to a marginal benefit of US$ 1.044 million per m^3/s of diverted flow.

For hydropower water use benefits, a zero slope (horizontal) marginal benefit function is considered and used for the optimization model. Energy rate function (*erf* in kWh/m^3) for each hydropower plant is developed first and then multiplied with water price for power production (US$/kWh), which gives the benefit from hydropower generation. The value of water use in the Selorejo power plant appears to be US$ 1.71 per 10^3m^3 (IDR 15.42 per m^3) of water, for Mendalan US$ 6.50 per 10^3m^3 (IDR 58.56 per m^3) of water and for Siman US$ 4.67 per 10^3m^3 (IDR 42.05 per m^3) of water.

The concept of flow-habitat-fish production relation is used for valuing water for fisheries use for the Teesta. Value of the fish production is considered equal to fishermen daily income for a certain time period e.g. month or year. Similarly, boatmen income is considered as the gross benefit from navigation water use. A quadratic relation between benefits in various seasons and corresponding flow is established, which actually serves as the total benefit function. Low flow season for the fishermen and high flow season for the boatmen are economically beneficial; however, severe low flow condition (which is currently taking place in February at the Teesta site) is not good for the fishermen group. Monthly maximum benefits that can be realized from the fisheries and navigation are about US$ 0.12 million at a flow of 290 m^3/s and US$ 0.01 million at a flow of 2000 m^3/s respectively. However, the maximum benefit generating flow level from both sectors does not coincide in time over a year. Nevertheless, the highest marginal benefit (US$ 1,237 for fisheries and US$ 10 for navigation per month at flow level zero) and subsequently the lowest total benefit for both the groups lie at very low flow level, when the off-stream irrigation demand is also very high.

A hyperbolic-tangent function is developed for the Selorejo reservoir recreation and fisheries benefit estimation. Using such function implies that benefit from reservoir activities entirely depends of reservoir storage for an already built reservoir. Maximum operating storage in Selorejo (i.e. 39.59×10^6 m^3) generates US$ 0.175 million benefit in a monthly basis whereas the lowest operating storage (i.e. $8.09 \times 10^6 \ m^3$) generates US$ 0.169 million; which shows that the variation in benefit due to change in Selorejo storage is quite small. In other words, elasticity of benefit to storage level is very small.

With the developed marginal benefit functions, optimal water allocations for both the study sites are identified using 'Aquarius' water allocation modeling platform. Aquarius is devoted to the spatial and temporal allocation of water among uses in a river basin. The model finds the economic efficiency of the system that entails a reallocation of the stream flows until the marginal return of all water uses are equal. The model is run and optimal water allocation is obtained for two cases, namely economic efficiency (water is allocated in order to maximize economic benefit, ignoring EF demand downstream) and environmental protection (with the constraints of EF demands). Several scenarios are developed and analyzed to realize the optimal as well as environmentally sound operation of the system. Analyses show the tradeoff between achieving two basic criteria of economic efficiency and environmental protection. Since EF is not a static choice, several EF values are also tested as constraints to see how the overall benefit changes due to change in EF levels.

In the case of Teesta, benefits from in-stream water direct uses are much smaller than off-stream irrigation benefit; hence instream uses cannot compete with offstream uses. The optimization model is first run with a medium level of EF (considered as +/- 1 RVA target); however, maximum in-stream water use benefit is observed lying to a higher flow level than this EF level. A higher EF is therefore provided to maximize in-stream benefits. Maintaining environmental flow results in considerable reduction in overall benefit for each scenario analyzed. In baseline scenario (existing operation policy i.e. maximum possible diversion to irrigation without considering EF) the overall benefit is US$ 43.830 million that comprises US$ 43.242 million from irrigation sector and US$ 0.588 million from instream sector. Instream water direct use benefit is only 1.36% of the overall benefit. The benefit reduced to US$ 34.58 million if EF (medium level with +/-1 SD RVA target) is ensured at the downstream. Overall benefit decreases by US$ 9.25 million in the baseline scenario which comprises a decrease in irrigation benefit of US$ 9.35 million and increase in in-stream benefit of US$ 0.10 million. When EF is not considered, options exist to increase overall benefit by augmenting flow, improving irrigation efficiency, or increasing irrigation land to some extent (analysis is done for 25% irrigation area extension). Considering EF, overall benefit can only be increased by improving irrigation efficiency to 60% (baseline: 40%). Groundwater use as supplemental to surface water irrigation is a solution to uphold the overall benefit, which is now been practiced in the TIP region. Groundwater potential for the region is also found satisfactory from the existing literature. Sound farm-support policy is required with regards to adoption of groundwater supplemental irrigation practice. In order to ensure EF, farmers might need to pay for groundwater irrigation and still cover the cost of production. Constraints with a lower level of EF downstream (with +/-1.5 SD RVA target) is also tested and it is observed that such EF provisioning results in less benefit reduction in irrigation (US$ 5.17 million loss) with still an increase in in-stream benefit (US$ 0.07 million gain) compared to baseline scenario.

Arguing for the minimum flow is in fact indicative of the resistance to allow water for in-stream uses. River ecosystems struggle with low flow and ultimately decline, which subsequently affects both the poor's livelihood (especially fishermen) and the environment. Even though the estimated in-stream benefit is relatively small compared to irrigation benefit, in-stream flow still provides livelihood to about 1,000 people without requiring massive capital investment nor O&M cost from any water management authorities or from the public sector. On the other hand, securing benefit from irrigation costs massive capital investment as well as O&M costs, all of which have been ignored in this research. Irrigation benefits consider net benefit gained from production at farm level, and ignored costs incurred at whole system level. After having developed the irrigation project with all the costs, TIP is providing livelihood to around 0.35 million farmers. The net benefit from TIP of US$ 165.85 million (Table B.4 in Appendix B); per capita income of the farmers per day is around US$ 1.23, which is easily comparable to per capita per day income of a fisherman (US$ 1.61, Table 6.4) or a boatman (US$ 3.39, Table 6.8). All such figures help realizing the actual value of water for each use and subsequently guarantee river flow for all uses to ensure socio-economic stability of the region. Also, the approach used here ignored the non-use, indirect benefits usually drawn from EF, which refer to biodiversity value, socio-cultural value, various supporting and regulating river ecosystem services (e.g. groundwater recharge, nutrient recycling, pollution and salinity control). Those may generate high benefits to society and change drastically the diagnosis on EF economic scope, magnitude and impact.

Current practice of water allocation in Konto produces maximum benefit but it also does not satisfy the environmental water requirements. Ensuring EF causes decrease in overall benefit in all the scenarios considered; however, benefit from flowing water is not accounted in this study. Since water use from hydropower is not redirected to the main course of river, the use should be treated as off-stream. No other direct use of in-stream flow is observed at Konto. Only in-stream uses are considered as reservoir recreation and fisheries; however, maximizing instream benefit results in overall decrease in basin benefit. For Konto basin, overall benefit in the baseline case (existing operation) is US$ 15.85 million. Ensuring EF incurs a reduction in benefit of US$ 1.07 million from the existing uses.

In contrast between the two case study basins, Teesta produces about three times higher benefit than Konto. However, unit water value (from off-stream sector) in Konto (US$ 0.078/m^3) is more than three times than that of Teesta (US$ 0.024/m^3). Teesta flows over almost a flat land having a high flow (mean annual flow more than 800 m^3/s) where construction of reservoir is not feasible but there is distinct in-stream uses. In contrast, topography of Konto basin is mountainous. Konto River has steep slope and less flow (mean annual flow about 10 m^3/s); it has a reservoir with hydropower. Management of water resources of the two rivers are again quite different. Konto is managed by PJT-I which is an individual body to manage water resources in Java Island, whereas Teesta is managed by the central body of Water Resources Management Authority in Bangladesh, namely BWDB. Implementing any change in operation can be thought much easier in Konto than in Teesta.

12.2 Conclusions

Following conclusions are drawn from the Teesta river study site:

- Water requirements for irrigation, capture fishery and navigation are estimated for monthly basis and benefit functions for the water uses are established. Off-stream water use (irrigation) benefits are observed considerably higher than in-stream water use (fishery and navigation) benefits. However, indirect and non-uses benefits of in-stream water have not been accounted. Further, the capital and O&M costs of irrigation have been ignored while estimating irrigation benefit function. Considering those costs will probably significantly reduce the actual benefits yielded by the irrigation sector;

- Assessment of EF requirements shows that currently EF is not maintained at the downstream point of the Teesta study site;
- From the water allocation model optimal benefits from the users are estimated. In the case of environmental protection, EF is used as a constraint in the allocation model. Three different levels (high, medium and low) of EF are tested to assess the change in benefit due to EF provisioning. Since in-stream benefits cannot compete with off-stream benefits for the Teesta site with the existing offstream uses, minimum EF requirements actually governs the allocation;
- For the case of water allocation with environmental or river health protection, it results in considerable reduction in water-use benefits, at least when in-stream non-use benefits and irrigation true costs are not accounted;
- Several scenarios are considered and it is found that improving irrigation efficiency is imperative to simultaneously fulfill irrigation demands and cater for environmental and other in-stream water uses;
- Even though the estimated in-stream benefit is much lower than off-stream benefits in particular for the case study sites, in-stream flow is critically important for local and regional socio-economy. Even allowing minimum EF helps sustaining livelihood for a considerable number of people, which will eventually leads to pro-poor water management.

Following conclusions are drawn from the Konto river study site:

- Water requirements and benefit functions for the water uses in the Konto River, namely hydropower, irrigation, M&I use and reservoir fishery and recreation are estimated. Water used in hydropower does not return back to the main course of Konto River and the released water from the most downstream hydropower plant is sent to Konto irrigation project. In this case hydropower water-use can be considered as offstream. No direct use of instream flow has been found in Konto case;
- Environmental flow requirements are assessed at Mendalan Sabo dam point and at most downstream point of Konto before it meets with the Brantas. It is observed that currently EF is not maintained at the Mendalan Sabo dam point round the year; however, since there is no major abstraction after Mendalan Sabo dam except small scale M&I uses, EF requirements at the most downstream point are normally met;
- Optimal water allocation model is set up and benefits after the water allocation are estimated. For the case of environmental protection, EF is used as constraint in the allocation model. Three different levels (high, medium and low) of EF are tested to realize the changes in benefits due to EF provisioning;
- For the case of water allocation with environmental or river health protection, it results in considerable reduction in basin benefits, at least when no instream flow use and related benefits are taken into consideration.

Overall conclusion:

- Successful implementation of EF is a challenge especially in developing countries where irrigation often gets priority to ensure food security; however, in-stream flow-dependent livelihood mainly for a poor section of the society is also significant, as the Teesta case has revealed in this study. Present study can be treated as a starting point to addressing such a challenging issue to consider food security as well as poor's livelihood in parallel by revealing water value for each uses and tradeoff between benefits from without and with consideration of EF;
- In-stream flows are not subjected to the same economic forces as those for off-stream water uses. The mathematical representation of social and environmental objectives is a complex phenomenon, which frequently leads to off-stream favored water management and that results in often irreversible degradation of the river health. Dyson et al. (2003) have rightly pointed out that "*the absence of environmental flow puts at risk the very existence of ecosystems, people and economies. The question is thus not whether environmental flows can be afforded, but whether and for how long a society can afford not to provide environmental flows*". Results from the research will significantly influence in forging connection between the 'triple bottom line parameters': economy, society and ecosystem.

12.3 Contributions of the research

A good number of researches have estimated the total value of the water uses in particular the in-stream uses and associated services rendered to society. Such valuation provides justification for water investment decision in general. However, total values are deficient to provide information in allocating water to its highest use value on margin. Hence, marginal benefit functions of all water uses are essentially required in this regard and the novelty of this study lies here.

In case of irrigation water valuation, many studies have measured the average value of water, or one single marginal value of water, such as a monetary value per cubic meter of water consumed, applied to field or withdrawn from a source. The value per unit of withdrawn/diverted-flow is very seldom considered, while river flow more realistically determines the amount of water that could be withdrawn or diverted for irrigation. Analysis showing the value of the discharge would be intriguing to the basin managers concerning water allocation decision in particular between off- and in-stream uses. Discharge is a critically important parameter for in-stream uses such as hydropower, fisheries, navigation and environmental flow demands, whereas off-stream demands mainly deal with certain volume of water. Hence, comparing the values of water for both sides (off-stream and in-stream) with a common denominator (discharge) is more interesting and easier to interpret even though discharge is location specific and care needs to be taken when comparing the discharge values at different locations. This dissertation contributed by estimating the marginal benefit function of irrigation water use in terms of discharge.

In the existing HEM studies, researchers have focused principally on hydropower generation and lake/reservoir recreations as the two main instream uses; however, those uses do not actually represent the benefit from instream flow. A literature review by Harou et al. (2009) could not find any estimation or application of economic benefit function of instream flow in any HEM study. In many developing countries, livelihoods of the poor are based upon instream flow, which therefore carries significant economic value as well as social importance. This study constitutes a first attempt to determine the marginal benefit functions for instream water uses (fisheries and navigation) and then to incorporate them into optimization modeling for water allocation.

12.4 Recommendations

12.4.1 Recommendations from the study

Following recommendations are made based on the results of the study:

For the Teesta Study site:

– Considering the importance of local livelihood and maintaining environmental and river health, environmental flow is recommended to provide in the downstream (Scenario S0 Case-II). Necessary policy formulation in participation with off- and in-stream water users is recommended to the Bangladesh Water Development Board;
– Both National Water Policy and National Water Management Plan recognize the environmental water requirements for the rivers in Bangladesh; however, river specific analysis was necessary due to inherent tradeoff involved. After this study implementation of EF at Teesta is recommended where the necessary tradeoff (comparison between Case-I & II for all scenarios considered) has been revealed;
– Improving irrigation efficiency is recommended for Teesta Irrigation Project management to increase the benefit level from both off-and in-stream sectors;
– There exists a huge data gap at the study site especially when it relates to in-stream water uses. Characteristics of the in-stream water uses and users need to be documented. River specific (not administrative unit wise) data collection for the in-stream water uses is necessary and recommended to the management authorities.

For the Konto River Basin study site:

– Even though the study did not recognize any instream water use, provisioning EF at the downstream part of Konto is recommended (S0 Case-II) to keep the river healthy and to maintain ecosystem integrity. Tradeoff is involved and that has been revealed, which will help the basin managers in provisioning EF;
– There exists a huge data gap for hydrological and especially for in-stream water uses. Hydrological data namely, inflow to reservoir, flow at different points at the downstream of Selorejo reservoir are required for hydrological modeling for the basin and hence recommended for collection to the PJT-I. Characteristics of the in-stream water uses and users need to be documented. Reservoir specific data collection for the reservoir recreation and fishery uses are necessary and recommended for collection to PJT-I.

12.4.2 Recommendations for future research

This dissertation cannot be seen as an end point in the analysis of optimal water allocation among competing water uses particularly for the case study rivers. There are several ways in which the performed analysis can be extended or fine-tuned:

- In this research benefits for water uses are estimated for seasonal or annual basis and then equally distributed into months to obtain monthly benefit function; however, this research provides some methodological options for future research and recommends field level study for water valuation which would lead to develop the monthly total benefit function for each water-use;
- Further research is also recommended to estimate the effect of water quality to water uses and subsequently to use-values and incorporation of those values to HEM;
- Estimated water-use benefits are short-term; however, long term environmental and social benefits of water use would be different. Moreover, for in-stream water uses, research needs to be extended to incorporate the benefit from non-use or in-direct in-stream water uses (such as flood mitigation, nutrient recycling and sediment redistribution, groundwater recharge, pollution dilution, maintaining biodiversity and ecosystem integrity etc.) and further incorporation of those benefits to the optimal water allocation model; economic valuation of ecosystem services is a daunting yet necessary task, and a hot spot in current research on ecosystems and resource use
- Possible distortion of the agricultural inputs market has not been taken into account in this research; however, this might affect the irrigation water benefit estimation. Future research should account this issue in RIM calculations;
- Estimated EF is based on hydrological methods; however, ecology based assessment of EF might change the EF demands and subsequently water allocation and benefits, which is strongly recommended for future research;
- Several scenarios are considered but achieving the scenarios (e.g. improving irrigation efficiency) involves different level of costs. However, such cost has been ignored in estimating the overall benefit for the scenarios considered. Future research is recommended to consider the cost of achieving the scenarios;
- The allocation model deals with the average demand and supply of water based on historical data set. However, both demand and supply are dynamic and subjected to change. Time value of money is also a dynamic parameter. Considering and incorporating those changes, dynamic HEM is further recommended.

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Appendix A. Discharge data of the Teesta River, Bangladesh

River name: Teesta Station name: Dalia Station ID: 291.5R

Table 12.1 Observed mean monthly discharge (m^3/s) at Dalia for the period of 1986 - 2006

Year	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Annual Mean
1986	210.7	159.4	135.8	256.0	423.6	1076.7	2048.7	1710.3	1729.0	897.7	388.5	252.6	774.0
1987	177.6	134.9	174.1	330.2	428.1	1280.7	2143.7	2889.7	1921.7	947.1	369.8	230.3	919.0
1988	163.0	165.3	193.7	268.9	474.4	928.8	2669.7	3607.7	1996.7	680.5	297.0	205.0	970.9
1989	183.2	189.0	200.3	270.3	905.2	2195.3	2861.3	1395.7	2302.7	1078.8	387.3	253.3	1018.5
1990	176.0	174.3	228.3	328.3	579.0	1790.0	2401.7	2483.0	1987.0	916.5	243.0	266.3	964.5
1991	239.3	201.0	352.7	408.3	591.3	1780.0	2500.0	2186.7	2360.0	747.3	382.7	273.3	1001.9
1992	193.7	137.0	180.0	270.3	664.7	798.0	1960.0	2017.4	1470.0	897.0	355.0	203.7	762.2
1993	210.0	174.7	165.7	187.3	652.0	1406.7	1870.0	2453.3	1613.3	1095.3	361.3	222.0	867.6
1994	134.7	154.3	154.0	263.3	422.7	1546.7	1227.7	1806.7	1283.3	669.7	378.7	241.3	690.3
1995	144.9	114.2	185.3	243.7	1166.3	1770.0	1810.0	1910.0	1923.3	712.7	650.0	190.3	901.7
1996	190.0	173.7	244.0	473.3	652.3	954.3	2166.7	2253.4	1306.7	745.0	344.7	282.0	815.5
1997	176.3	134.0	179.3	204.4	345.0	1280.5	2056.4	1700.0	1513.3	498.7	212.7	70.6	697.6
1998	40.4	50.6	72.5	156.0	302.3	1433.3	1140.0	2546.7	1692.7	653.3	233.3	258.7	715.0
1999	70.3	74.7	37.8	113.8	514.2	958.3	1807.8	2427.1	1285.0	838.4	229.5	80.3	703.1
2000	107.9	74.5	73.5	247.4	659.0	1955.9	3057.8	3766.4	4365.6	798.6	209.5	91.8	1284.0
2001	20.2	21.8	12.5	69.8	648.5	3633.6	1492.6	2101.2	1440.1	966.7	382.2	49.5	903.2
2002	33.1	24.7	46.8	145.4	257.7	1269.6	2272.8	1704.8	961.3	362.7	248.3	58.2	615.4
2003	48.1	28.3	46.2	96.3	253.6	1171.1	1785.4	1545.7	1466.6	931.1	294.1	195.7	655.2
2004	78.2	77.7	94.2	418.1	682.5	983.5	1239.0	1317.4	830.7	541.8	228.0	172.7	573.8
2005	70.2	71.1	96.9	192.3	444.6	762.8	1170.5	801.6	544.6	441.0	207.4	125.6	410.7
2006	47.7	48.0	40.2	99.9	308.9	842.6	1306.0	1052.9	1221.2	558.1	276.0	150.0	498.4
Avg	129.3	113.5	138.8	240.2	541.7	1419.9	1951.8	2079.9	1676.9	760.9	318.0	184.4	796.3
Max	239.3	201.0	352.7	473.3	1166.3	3633.6	3057.8	3766.4	4365.6	1095.3	650.0	282.0	1284.0
Min	20.2	21.8	12.5	69.8	253.6	762.8	1140.0	801.6	544.6	362.7	207.4	49.5	410.7

Source: BWDB Database, 2008

River name: Teesta Station name: Kaunia Station ID: 294

Table 1.2 Observed mean monthly discharge (m^3/s) at Kaunia for the period of 1960 - 2006

Year	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Annual mean
1967	141.5	114.4	131.0	169.0	413.8	1964.7	2236.5	1414.3	1568.5	995.9	348.4	165.5	805.3
1968	134.4	110.9	140.8	188.6	439.0	1258.5	2914.8	2245.1	1839.7	1794.4	353.3	201.9	968.4
1969	137.1	118.6	112.0	193.2	497.0	1834.2	2333.9	1790.0	1344.8	228.8	43.8	17.0	720.9
1970	9.4	83.2	124.8	221.6	465.3	1895.6	2898.1	2385.5	1608.0	983.7	306.6	195.2	931.4
1971	138.9	151.1	169.7	275.3	646.4	1557.0	2503.9	2192.3	1514.0	817.6	305.8	185.9	871.5
1972	139.7	141.3	178.9	329.0	827.4	1218.5	2109.7	1999.0	1420.0	651.5	305.1	176.5	791.4
1973	140.6	131.4	188.0	273.0	527.0	2243.2	1568.0	2313.9	1828.3	787.7	328.1	211.5	878.4
1974	165.9	150.2	170.2	264.3	663.0	1526.2	3130.0	2382.9	1999.7	1506.8	394.0	159.4	1042.7
1975	136.4	112.3	119.3	293.4	634.2	1181.3	2205.2	1314.8	2052.3	1007.6	411.5	257.8	810.5
1976	168.1	166.0	172.9	178.3	471.8	1187.8	2430.0	2597.3	1476.7	829.3	392.4	227.8	858.2
1977	186.0	159.2	145.6	330.4	677.2	1778.3	2391.3	3442.9	1600.3	1409.1	497.2	280.6	1074.8
1978	208.4	181.5	179.5	256.2	641.2	1541.6	2143.5	2137.2	1698.2	722.7	329.4	258.4	858.2
1979	168.1	134.4	111.9	203.9	372.4	540.3	1936.1	1801.0	1753.6	1009.5	348.5	293.7	722.8
1980	201.9	160.1	187.4	350.0	538.2	1296.9	1991.6	2105.8	1760.7	803.1	311.3	201.5	825.7
1981	155.0	131.0	156.4	243.4	499.0	803.3	2095.8	2269.7	1738.1	556.7	288.6	194.4	760.9
1982	148.8	147.1	161.4	236.5	343.8	1302.6	2547.6	1634.2	1482.3	470.8	323.6	216.7	751.3
1983	161.3	174.7	214.9	252.3	545.0	1268.9	2583.2	1726.8	1884.0	913.1	290.8	179.3	849.5
1984	175.3	134.9	154.6	181.2	525.7	1493.7	2721.6	1773.2	2854.3	886.2	394.6	245.5	961.7
1985	179.0	182.7	195.7	295.3	488.0	1591.9	3345.5	1786.8	2227.0	1363.9	643.8	378.0	1056.5
1986	231.4	161.9	151.9	226.8	362.5	893.1	1681.6	1681.6	2023.0	784.7	316.3	226.0	728.4
1987	185.9	126.5	168.4	285.8	464.6	1247.3	2730.3	3224.2	2461.3	1135.9	457.6	260.9	1062.4
1988	177.0	149.6	182.0	338.1	476.9	907.9	2738.0	3658.1	2033.1	730.3	301.3	178.1	989.2
1989	156.6	151.1	166.6	210.8	847.2	1919.0	2567.4	1951.0	2408.7	975.6	390.2	232.4	998.0
1990	169.5	159.0	199.5	366.7	642.1	1710.4	2485.8	2368.7	1397.3	932.8	321.7	177.3	910.9
1991	158.8	165.2	141.8	214.3	433.3	1854.3	2385.2	2584.2	3156.0	975.3	338.9	216.5	1052.0
1992	148.9	145.3	166.8	225.1	388.9	760.3	2351.0	2113.3	1278.7	757.0	295.4	206.4	736.4
1993	158.8	155.8	126.1	201.9	541.4	1111.8	2235.5	2716.5	1738.3	1183.3	407.2	233.6	900.8

Table A.2 Observed mean monthly discharge (m^3/s) at Kaunia for the period of 1960 – 2006 (Cont'd)

Year	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Annual mean
1994	175.8	149.5	188.5	234.2	377.5	1154.9	1463.9	1441.2	1286.9	653.6	282.1	173.5	631.8
1995	140.7	138.8	177.5	257.5	729.5	1911.2	3154.5	2288.4	1975.7	878.9	451.1	257.3	1030.1
1996	198.1	155.8	175.2	202.8	620.7	1166.4	3650.0	2656.0	1990.0	870.7	359.1	243.9	1024.1
1997	162.6	130.7	169.4	241.1	368.4	1228.0	1707.0	1724.0	1716.9	843.7	312.3	180.4	732.0
1998	60.5	48.8	72.5	228.2	459.9	1815.1	3442.1	3766.0	2288.5	1239.0	313.6	313.4	1170.6
1999	94.5	83.4	41.1	123.1	588.9	1724.9	2573.1	2822.9	1659.9	1135.6	328.1	121.9	941.5
2000	142.0	94.7	116.5	304.8	843.4	2100.2	2640.4	3029.4	2366.0	607.7	207.5	77.9	1044.2
2001	20.6	16.4	10.9	42.4	293.8	1398.0	1330.5	1441.5	1897.0	1010.3	382.2	153.0	666.4
2002	35.0	34.1	32.1	172.3	379.0	1062.4	2404.0	1898.9	1000.7	508.2	178.5	100.1	650.4
2003	36.0	18.7	36.3	135.1	322.6	1495.2	2845.2	1970.0	1454.2	776.4	379.9	400.8	822.5
2004	40.0	25.0	183.6	172.4	170.2	1170.2	1922.6	1651.4	1435.7	901.6	240.0	184.0	674.7
2005	48.0	29.2	67.6	201.5	429.2	1088.3	2110.7	1989.7	1186.3	908.6	264.9	130.7	704.6
2006	62.2	18.5	44.2	151.4	429.3	883.9	1253.3	1062.0	1196.0	574.6	290.3	219.2	515.4
Avg	137.5	121.1	140.8	231.8	509.6	1402.2	2394.0	2183.8	1790.0	903.1	335.9	208.3	863.2
Max	231.4	182.7	214.9	366.7	847.2	2243.2	3650.0	3766.0	3156.0	1794.4	643.8	400.8	1170.6
Min	9.4	16.4	10.9	42.4	170.2	540.3	1253.3	1062.0	1000.7	228.8	43.8	17.0	515.4

Source: BWDB Database, 2008

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Appendix B. Irrigation water requirements and irrigation water value at TIP

Table 1.3 Monthly irrigation requirements (mm) for the crops grown at TIP (Total irrigated area of TIP is 111,732 ha)

	Aman		Aus		Boro		Cabbage	Cauliflower	Potato	Tobacco	Tomato	Wheat	Total irrigation require-ment (mm)	Total irrig requirement (mm) with 40% efficiency	Total irrigation requirement (mm/d) with 40% efficiency
% area	4.92	98.4	0.39	7	2.7	54.5	0.7	0.7	6.9	8.7	0.8	11.8			
Month	Nur	LP + CWR +SP	Nur	LP + CWR +SP	Nur	LP + CWR +SP									
Jan	0.0	0.0	0.0		0.0	188.0	84.8	80.3	93.1	79.9	92.9	88.0	128.1	320.3	10.3
Feb	0.0	0.0	0.0		0.0	199.6	37.8	98.5	101.5	107.1	102.3	105.8	139.4	348.4	12.4
Mar	0.0	0.0	0.0	0.0	0.0	200.0	0.0	65.1	37.2	69.4	39.4	39.3	123.0	307.5	9.9
Apr	0.0	0.0	88.0	110.0	0.0	32.2	0.0	0.0	0.0	0.0	0.0	0.0	25.6	64.0	2.1
May	0.0	0.0	0.0	52.1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	3.6	9.1	0.3
Jun	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Jul	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Aug	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Sep	0.0	0.0	0.0		0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Oct	0.0	0.0	0.0		0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Nov	0.0	120.9	0.0		46.0	53.1	45.0	48.1	32.2	0.0	38.6	11.6	153.7	384.4	12.8
Dec	0.0	28.9	0.0		33.1	266.7	60.3	54.0	59.8	31.4	57.0	30.3	186.4	465.9	15.0
subtotal	0.0	149.8	88.0	162.1	79.1	939.7									
Total		149.8		250.1		1018.8	227.9	346.0	323.7	287.8	330.1	275.0	756.2	1890.6	

Nur = Nursery
LP = Land preparation
CWR = crop water requirement
SP = Seepage and percolation

Table 1.4 Monthly irrigation requirements in terms of discharge (m^3/s) for the crops grown at TIP (Total irrigated area of TIP is 111,732 ha)

Month	Aman	Aus	Boro	Cabbage	Cauliflower	Potato	Tobacco	Tomato	Wheat	Total	Total with 40% efficiency
Jan	0.00	0.00	42.74	0.3	0.23	2.7	2.9	0.3	4.3	53.5	133.6
Feb	0.00	0.00	50.25	0.1	0.32	3.2	4.3	0.4	5.8	64.4	160.9
Mar	0.00	0.00	45.48	0.0	0.19	1.1	2.5	0.1	1.9	51.3	128.3
Apr	0.00	3.85	7.57	0.0	0.00	0.0	0.0	0.0	0.0	11.4	28.6
May	0.00	1.70	0.00	0.0	0.00	0.0	0.0	0.0	0.0	1.7	4.3
Jun	0.00	0.00	0.00	0.0	0.00	0.0	0.0	0.0	0.0	0.0	0.0
Jul	0.00	0.00	0.00	0.0	0.00	0.0	0.0	0.0	0.0	0.0	0.0
Aug	0.00	0.00	0.00	0.0	0.00	0.0	0.0	0.0	0.0	0.0	0.0
Sep	0.00	0.00	0.00	0.0	0.00	0.0	0.0	0.0	0.0	0.0	0.0
Oct	0.00	0.00	0.00	0.0	0.00	0.0	0.0	0.0	0.0	0.0	0.0
Nov	51.30	0.00	13.01	0.1	0.14	1.0	0.0	0.1	0.6	66.3	165.7
Dec	11.86	0.00	61.01	0.2	0.16	1.7	1.1	0.2	1.5	77.8	194.4
Average											135.8

Table 1.5 Crop Budget analysis for the irrigated crops at TIP

Agriculture production Input (unit)		Labor man.d/ha	Bullock pair.d/ha	Seed require-ment kg/ha	*seed unit price tk/kg*	Urea kg/ha	TSP kg/ha	MP kg/ha	Zinc kg/ha	Sulfur kg/ha	Pesticide kg/ha	Total input cost (10^6 Tk)	Input cost for the crops (Tk/ha)	Input cost for the crops ($/ha)
Agriculture production Input unit price (Tk)		130	120			12	80	60	8.4	6	280			
Crops	Area irrig-ated (ha)	Input requirements for the crops (*except seed unit price column*)												
Aman LV	11,273	149	30	25	*30*	60	35	20	0	0	1.5	325.34	28,860	406
Aman HYV	98,714	165	35	21	*30*	100	50	30	5	50	2	3,374.24	34,182	481
Aus HYV	7,820	170	35	21	*30*	120	35	20	5	30	2	259.25	33,152	467
Boro HYV	60,837	200	45	23.5	*30*	200	90	50	7.5	65	5	2,832.45	46,558	656
W.Veg	2,495	201	50	1.5	*1200*	80	50	30	0	0	5	105.02	42,090	593
Potato	7,665	185	45	1200	*20*	80	60	50	0	60	5	490.33	63,970	901
Tobacco	9,771	240	50	0.1	*59,900*	100	50	35	3	20	5	508.44	52,035	733
Wheat	13,167	100	30	90	*35*	80	60	30	0	0	0	359.59	27,310	385
Total Cropped Area (ha)	211,742													
Net Area (ha)	111,732													
Total cost (10^6 Tk) (10^6 US$)												8,254.65 (116)		
Cost per ha (Tk/ha) ($/ha)													73,879 (1041)	

Source: BWDB, 2005

Table 1.6 Crop wise and at the project level irrigation water value

Crops	Area irrigated (ha)	Yield (t/ha)	Unit output value (Tk/kg)	Total output value (10^6 Tk)	Output value (Tk/ha)	Output value including rice straw (Tk/ha)	Input cost (Tk/ha)	WRF (m^3/ha/yr)	WWR (m^3/ha/yr)	Diverted water value (Tk/m^3)
T. Aman LV	11,273	2.67	14	421.38	37,380	39,930	28,860	1,504	3,760	2.94
T. Aman HYV	98,714	3.85	13	4,940.64	50,050	52,050	34,182	1,504	3,760	4.75
Aus HYV	7,820	3.19	12	299.35	38,280	40,280	33,152	2,500	6,250	1.14
Boro HYV	60,837	4.5	13	3,558.96	58,500	60,500	46,558	10,190	25,475	0.55
W. Veg	2,495	8	8	159.68	64,000	64,000	42,090	3,013	7,533	2.91
Potato	7,665	15	5	574.88	75,000	75,000	63,970	3,237	8,093	1.36
Tobacco	9,771	1.25	60	732.83	75,000	75,000	52,035	2,878	7,195	3.19
Wheat	13,167	2.5	22	724.19	55,000	55,000	27,310	2,750	6,875	4.03
Rice Straw LV	11,273	1.7	1.5	28.75	2,550	-------				
Rice Straw HYV	167,371	2	1	334.74	2,000	-------				
Total cropped area (ha)	211,742									
Net irrigated Area (ha)	111,732									
Total output value (10^6Tk)				11,775.39 (165.85x10^6 US$)						
Output value Tk/ha					105,390					

Net income (Tk/ha) = 105390 – 73879 = 31,511 (full supply from river) ($444/ha)

Total water diversion requirement (m^3/ha/yr) = 18,906

Value of water (Tk/m^3) = 1.67 ($0.023/$m^3$)

River water availability (m^3/ha/yr) = 12,077

GW pumping requirment (m^3/ha/yr) = (18,906 – 12,077)*0.4/0.7 = 3,900 [GW use efficiency 70%]

Cost of GW pumping (Tk/ha) @0.6 Tk/m^3) = 2,340 ($33/ha)

Net income with GW use (Tk/ha) = 29,171 ($411/ha)

Value of water value with GW use (Tk/m^3) = 2.42 ($0.034/$m^3$)

Appendix C. Questionnaire survey and results for the instream water use benefits at Teesta

Questionnaire used for the primary survey on instream water users at the Teesta site

<u>Survey design</u>

Selection of focus group – two principal groups were targeted, (i) subsistence fishermen and (ii) boatmen

Mode of survey – personal interview and individual questionnaire.

Elicitation method – amount of income each individual receives from fish-catching or boating.

<u>Questionnaire in detail</u>

Dependency on river flow:

- How do you define flow level within a year?
  - Seasonal distribution? (how many season? Season spreading over which months in calendar year?)
  - Monthly distribution?
- What is your income per day in different flow levels as you mentioned in answer to the last question?
  - In each season …?
  - In each month…..?
- What is your alternative occupational choice if income falls very short or to an unsatisfactory level to you?
  - Agriculture labor sell
  - Rickshaw pulling
  - No shift from this occupation
  - Any other occupation
- Do you have any agricultural land?

Socio-demographic:

- Name & address
- Age (years)
- Occupation – fisherman or boatman
- Experience in current occupation (years)
- Education (years of schooling)
- Family size (number of family members)
- Sex – male or female
- Working days per week (number of days)
- Individual or group fishing (only for fishermen)

Main results from General linear model (GLM) repeated measures for fishermen group

The dependent variables, income measured for multiple times are presented as a factor name 'income' in the GLM. Predictor variables are the factors except flow. The GLM repeated measures model is employed to test the main effects on repeated measures of between-subjects (grouping) factors and the main effects of within-subjects factors. Results are presented in Tables C.1 and C.2. Results show that there are no significant interaction between income and other factors.

Table 1.7 Test of between subject factors used in GLM (case of Fishermen group)

Transformed Variable: Average

Source	Type III Sum of Squares	df	Mean Square	F	Sig.
Intercept	2316411.029	1	2316411.029	2972.003	.000
Age	113.865	2	56.932	.073	.930
Experience	394.564	1	394.564	.506	.482
Education	1746.316	2	873.158	1.120	.339
Fam_size	6846.380	3	2282.127	2.928	.049
Activity_day	1247.284	1	1247.284	1.600	.215
Catch_mode	333.015	1	333.015	.427	.518

Table 1.8 Tests of within subject effect (case of Fishermen group)

Source		Type III sum of squares	Df	Mean square	F	Sig
Income	Sphericity Assumed	477050.883	4	119262.721	715.950	.000
	Greenhouse-Geisser	477050.883	2.072	230285.225	715.950	.000
	Huynh-Feldt	477050.883	4.000	119262.721	715.950	.000
	Lower-bound	477050.883	1.000	477050.883	715.950	.000
Income * Age	Sphericity Assumed	1060.723	8	132.590	.796	.607
	Greenhouse-Geisser	1060.723	4.143	256.020	.796	.536
	Huynh-Feldt	1060.723	8.000	132.590	.796	.607
	Lower-bound	1060.723	2.000	530.361	.796	.460
Income * Experience	Sphericity Assumed	891.971	4	222.993	1.339	.259
	Greenhouse-Geisser	891.971	2.072	430.578	1.339	.270
	Huynh-Feldt	891.971	4.000	222.993	1.339	.259
	Lower-bound	891.971	1.000	891.971	1.339	.256
Income * Education	Sphericity Assumed	6231.660	8	778.958	4.676	.000
	Greenhouse-Geisser	6231.660	4.143	1504.095	4.676	.002
	Huynh-Feldt	6231.660	8.000	778.958	4.676	.000
	Lower-bound	6231.660	2.000	3115.830	4.676	.017
Income * Fam_size	Sphericity Assumed	6276.394	12	523.033	3.140	.001
	Greenhouse-Geisser	6276.394	6.215	1009.928	3.140	.008
	Huynh-Feldt	6276.394	12.000	523.033	3.140	.001
	Lower-bound	6276.394	3.000	2092.131	3.140	.039
Income * Activity_day	Sphericity Assumed	209.218	4	52.304	.314	.868
	Greenhouse-Geisser	209.218	2.072	100.995	.314	.739
	Huynh-Feldt	209.218	4.000	52.304	.314	.868
	Lower-bound	209.218	1.000	209.218	.314	.579
Income * Catch_mode	Sphericity Assumed	1858.616	4	464.654	2.789	.029
	Greenhouse-Geisser	1858.616	2.072	897.204	2.789	.067
	Huynh-Feldt	1858.616	4.000	464.654	2.789	.029
	Lower-bound	1858.616	1.000	1858.616	2.789	.105

Main results from General linear model (GLM) repeated measures for boatmen group

Similar manner of fishery, the dependent variables, income measured for multiple times are presented as a factor name 'income' in the GLM. Predictor variables are the factors except flow. The GLM repeated measures model is employed to test the main effects on repeated measures of between-subjects (grouping) factors, the main effects of within-subjects factors, interaction effects between factors. Results are presented in Tables C.3 and C.4. Results show that there are no significant interaction between income and other factors except the catching mode.

Table 1.9 Tests of between-subjects effects for factors used in GLM (case of Boatmen group)

Transformed Variable: Average

Source	Type III Sum of Squares	df	Mean Square	F	Sig.
Intercept	2186913.617	1	2186913.617	481.633	.000
Age	16.667	1	16.667	.004	.955
Experience	13275.000	2	6637.500	1.462	.334
Education	.000	0	.	.	.
Fam_size	21549.784	3	7183.261	1.582	.326
Activity day	208.333	1	208.333	.046	.841

Table 1.10 Tests of within-subjects effects (case of Boatmen group)

Source		Type III Sum of Squares	df	Mean Square	F	sig
Income	Sphericity Assumed	1064730.772	2	532365.386	412.486	.000
	Greenhouse-Geisser	1064730.772	1.991	534713.505	412.486	.000
	Huynh-Feldt	1064730.772	2.000	532365.386	412.486	.000
	Lower-bound	1064730.772	1.000	1064730.772	412.486	.000
Income * Age	Sphericity Assumed	2033.333	2	1016.667	.788	.487
	Greenhouse-Geisser	2033.333	1.991	1021.151	.788	.487
	Huynh-Feldt	2033.333	2.000	1016.667	.788	.487
	Lower-bound	2033.333	1.000	2033.333	.788	.425
Income * Experience	Sphericity Assumed	11050.000	4	2762.500	2.140	.167
	Greenhouse-Geisser	11050.000	3.982	2774.685	2.140	.167
	Huynh-Feldt	11050.000	4.000	2762.500	2.140	.167
	Lower-bound	11050.000	2.000	5525.000	2.140	.233
Income * Education	Sphericity Assumed	.000	0	.	.	.
	Greenhouse-Geisser	.000	.000	.	.	.
	Huynh-Feldt	.000	.000	.	.	.
	Lower-bound	.000	.000	.	.	.
Income * Fam_size	Sphericity Assumed	18919.080	6	3153.180	2.443	.121
	Greenhouse-Geisser	18919.080	5.974	3167.088	2.443	.121
	Huynh-Feldt	18919.080	6.000	3153.180	2.443	.121
	Lower-bound	18919.080	3.000	6306.360	2.443	.204
Income * Activity_day	Sphericity Assumed	1979.167	2	989.583	.767	.496
	Greenhouse-Geisser	1979.167	1.991	993.948	.767	.495
	Huynh-Feldt	1979.167	2.000	989.583	.767	.496
	Lower-bound	1979.167	1.000	1979.167	.767	.431

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Appendix D. Environmental flow assessment for The Teesta

Monthly flow duration curves at Kaunia point

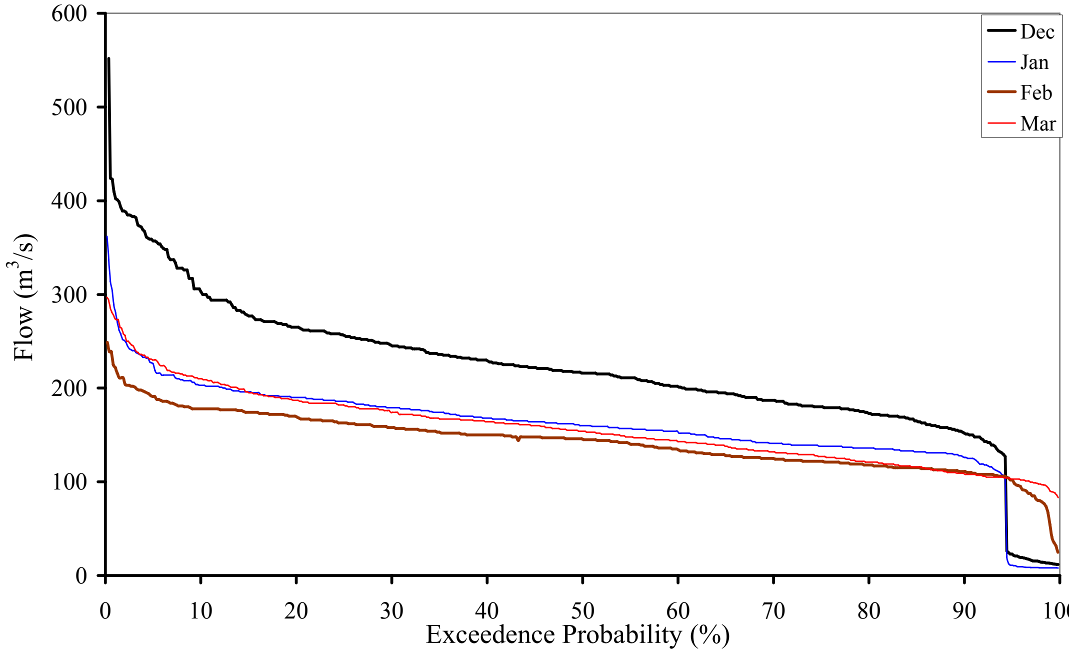


Figure 1.1 Flow Duration Curves for the low flow season (December - March) for the Teesta at Kaunia based on daily flow for the period of 1967 – 1990

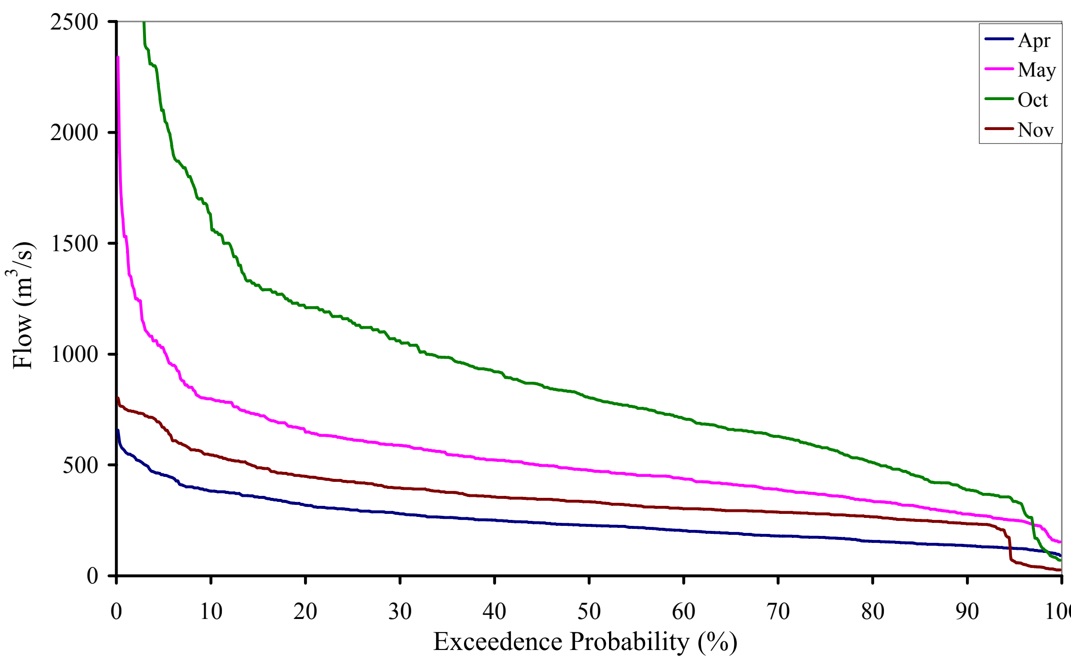


Figure 1.2 Flow Duration Curves for the intermediate flow season (December - March) for the Teesta at Kaunia based on daily flow for the period of 1967 – 1990

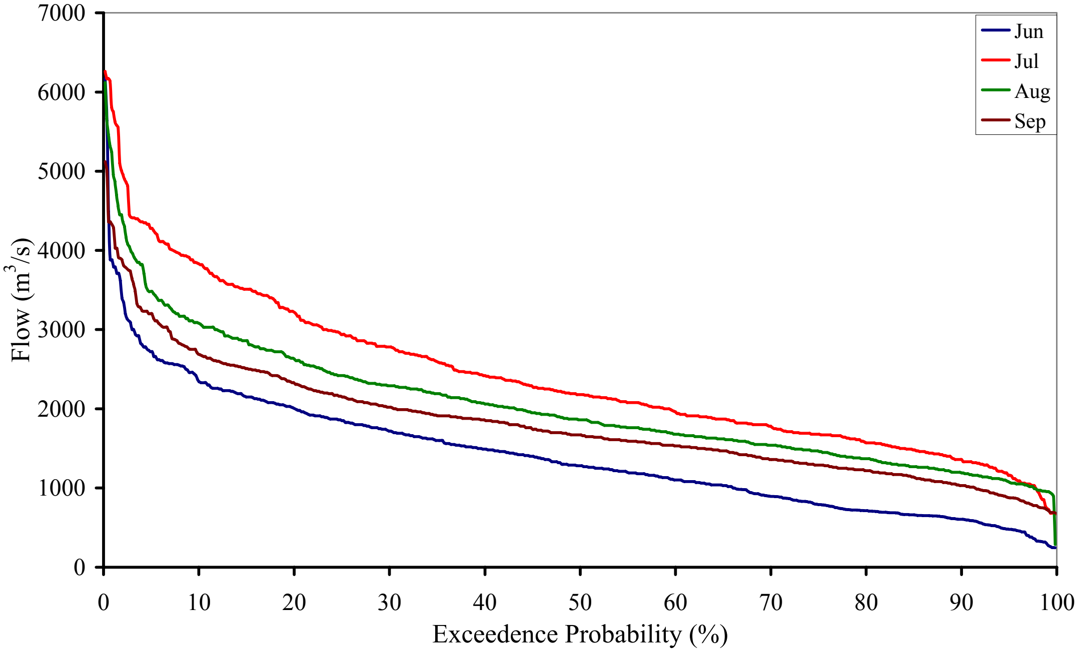
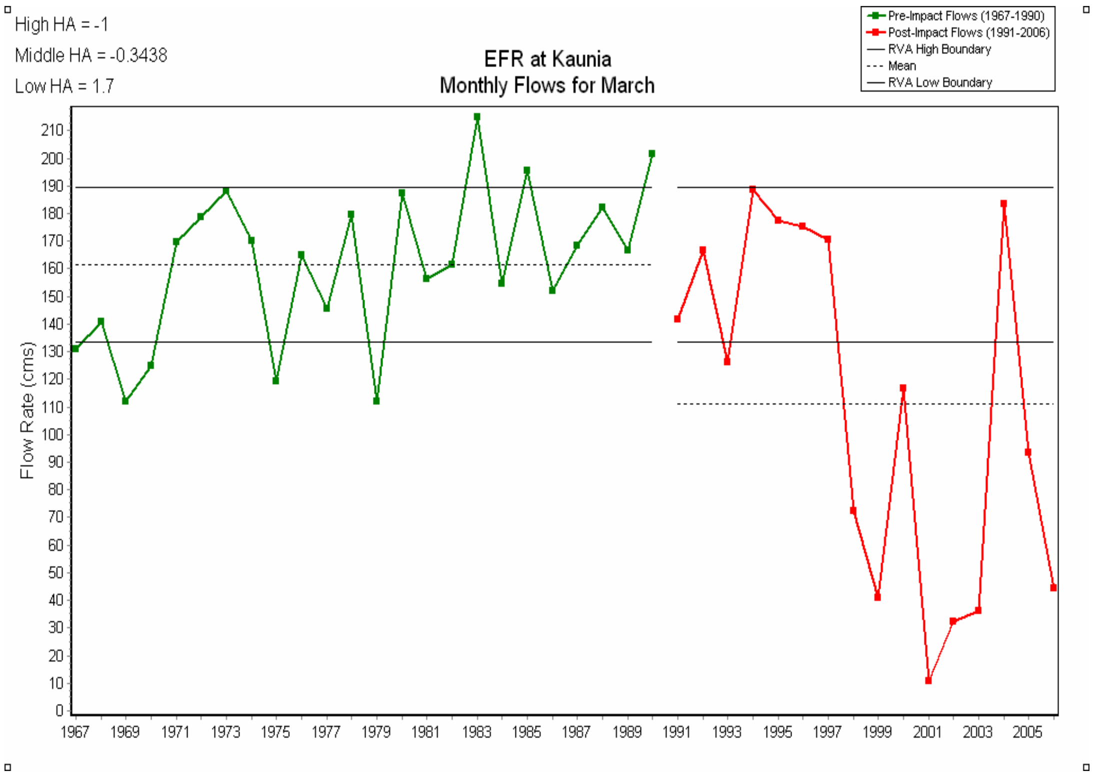


Figure 1.3 Flow Duration Curves for the high flow season (December - March) for the Teesta at Kaunia based on daily flow for the period of 1967 – 1990

Mean monthly flows with RVA targets for the months of March to December at Kaunia point.



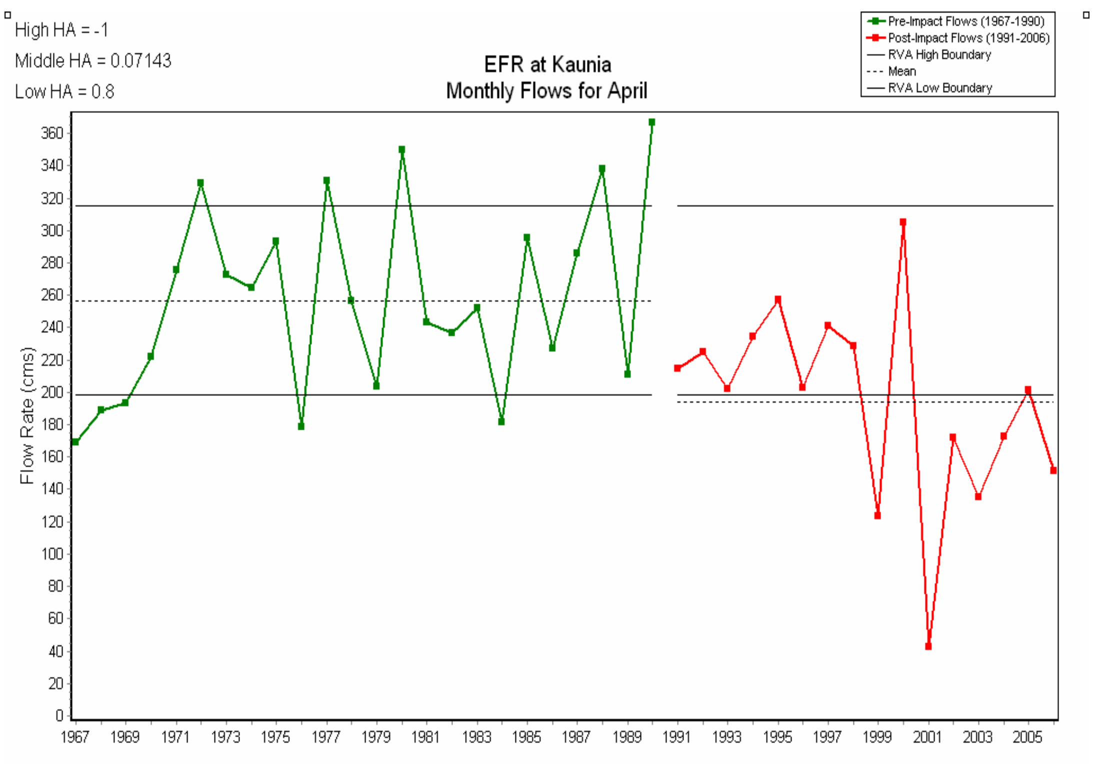
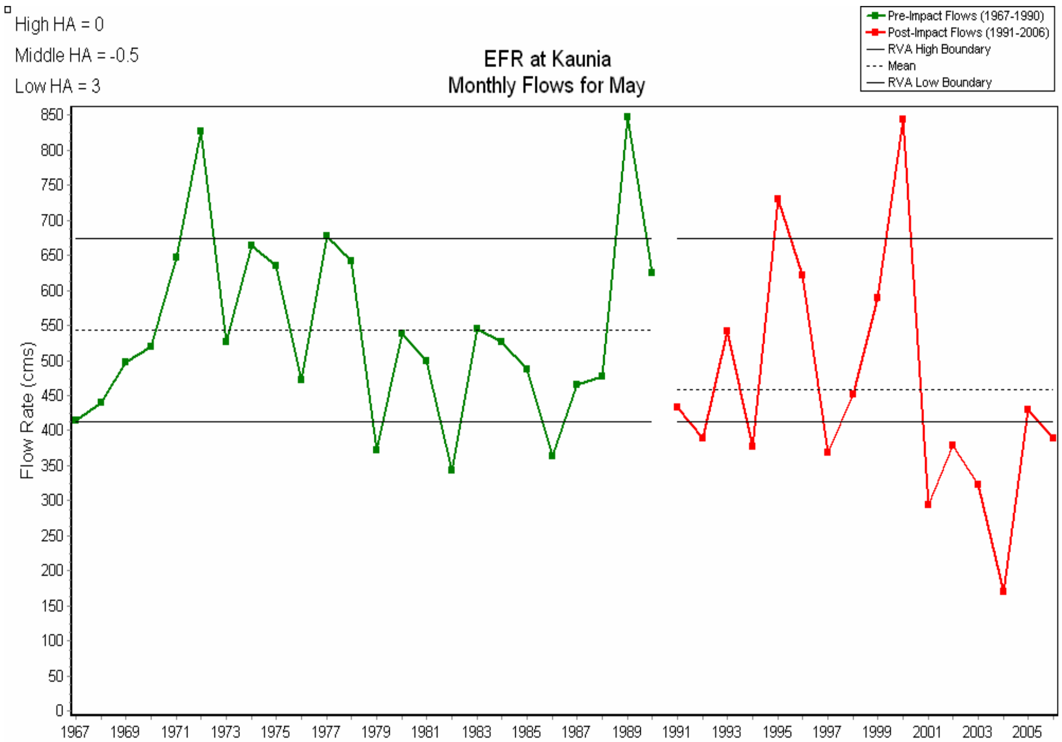


Figure 1.4 Mean monthly flows with RVA targets and IHA values for the months of March to December at Kaunia of the Teesta River



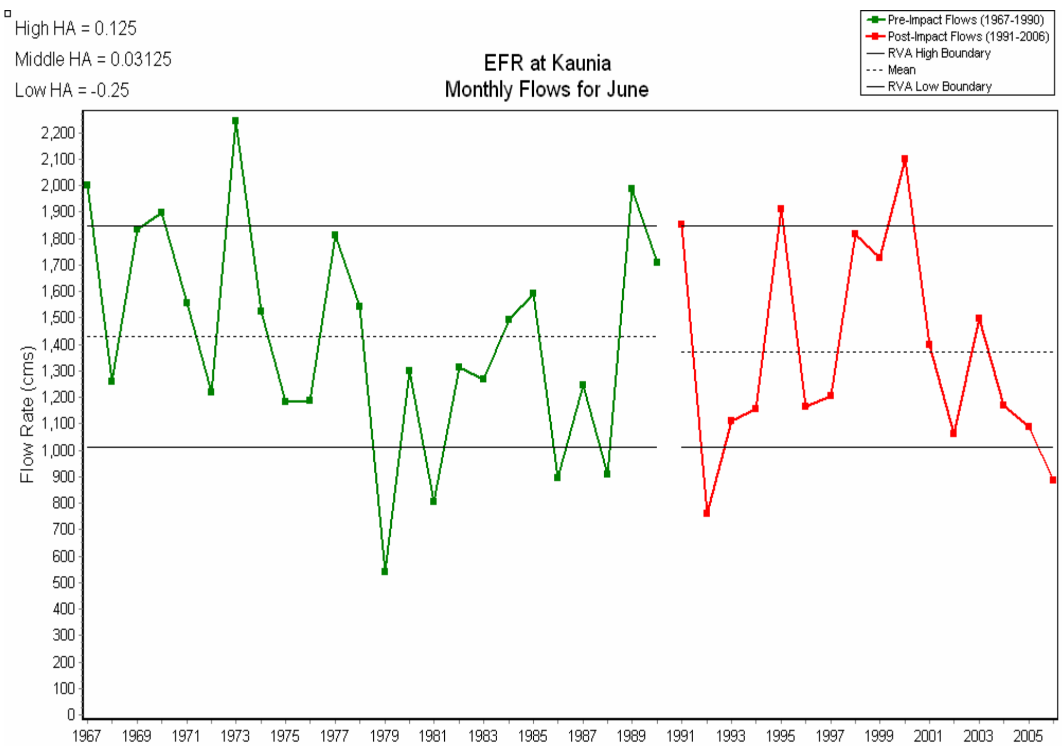
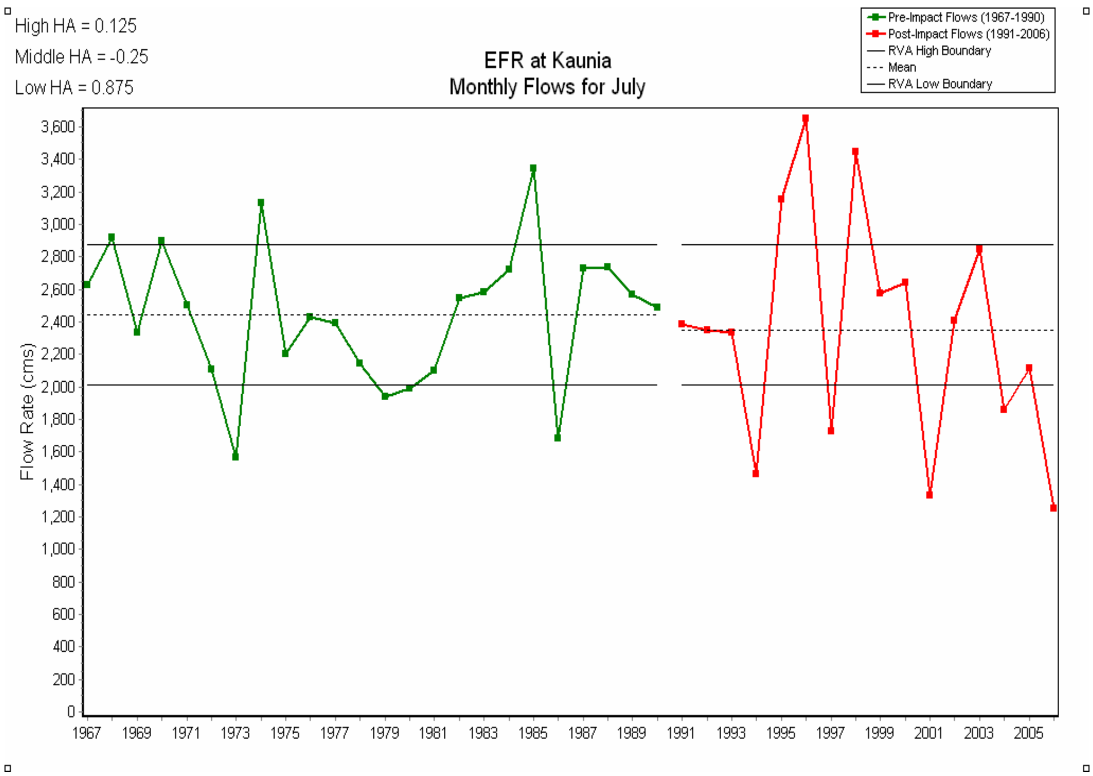


Figure D.4 Mean monthly flows with RVA targets and IHA values for the months of March to December at Kaunia of the Teesta River (Cont'd)



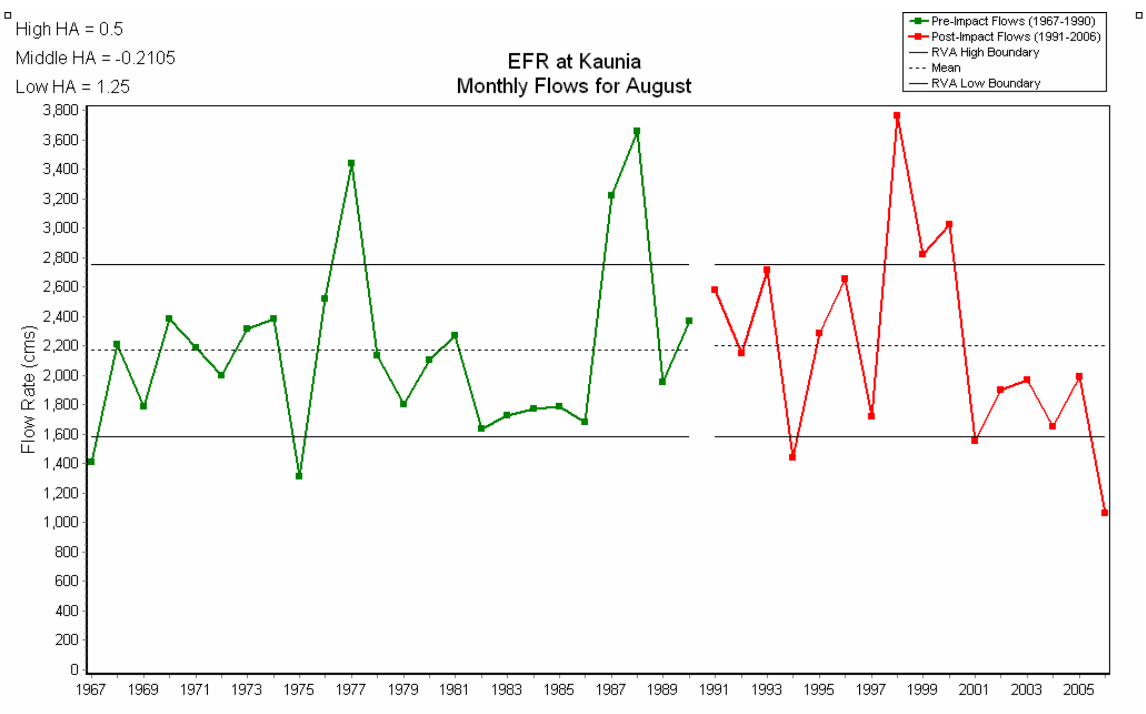
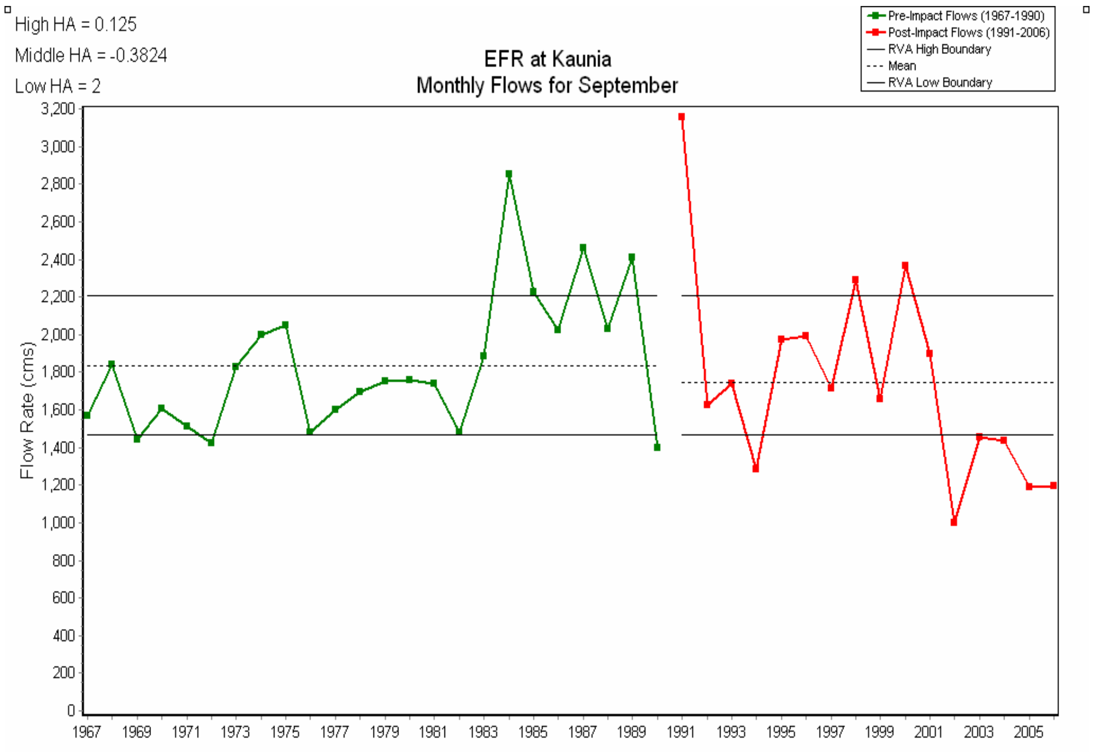


Figure D.4 Mean monthly flows with RVA targets and IHA values for the months of March to December at Kaunia of the Teesta River (Cont'd)



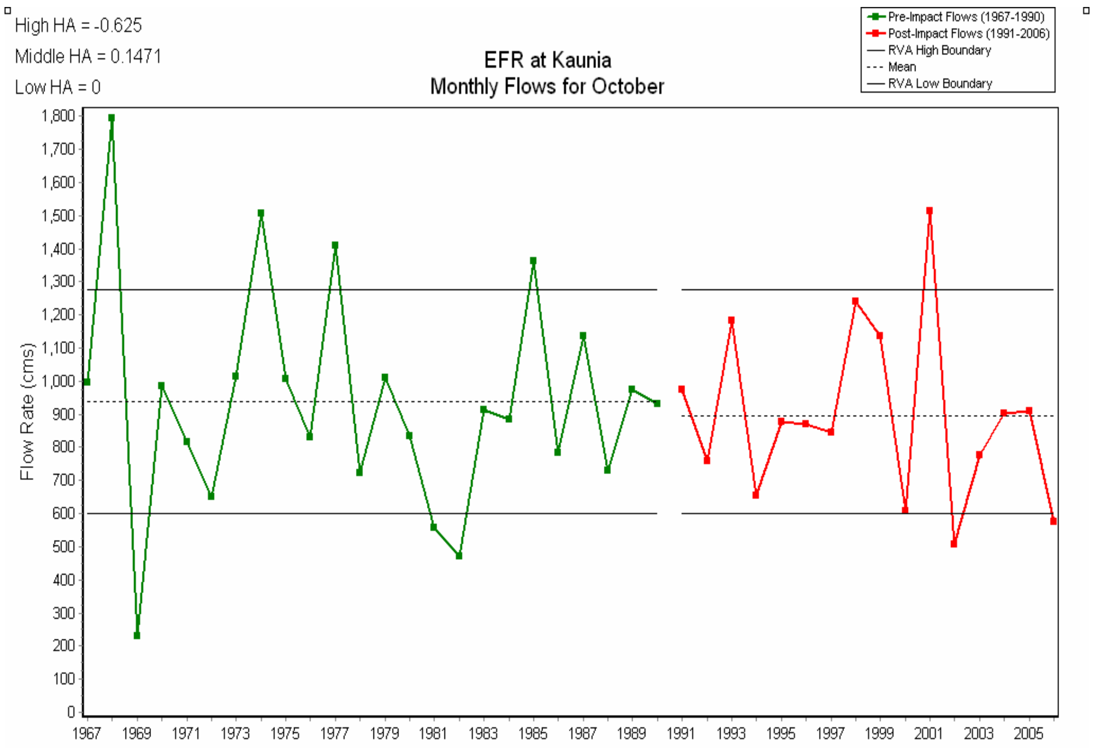
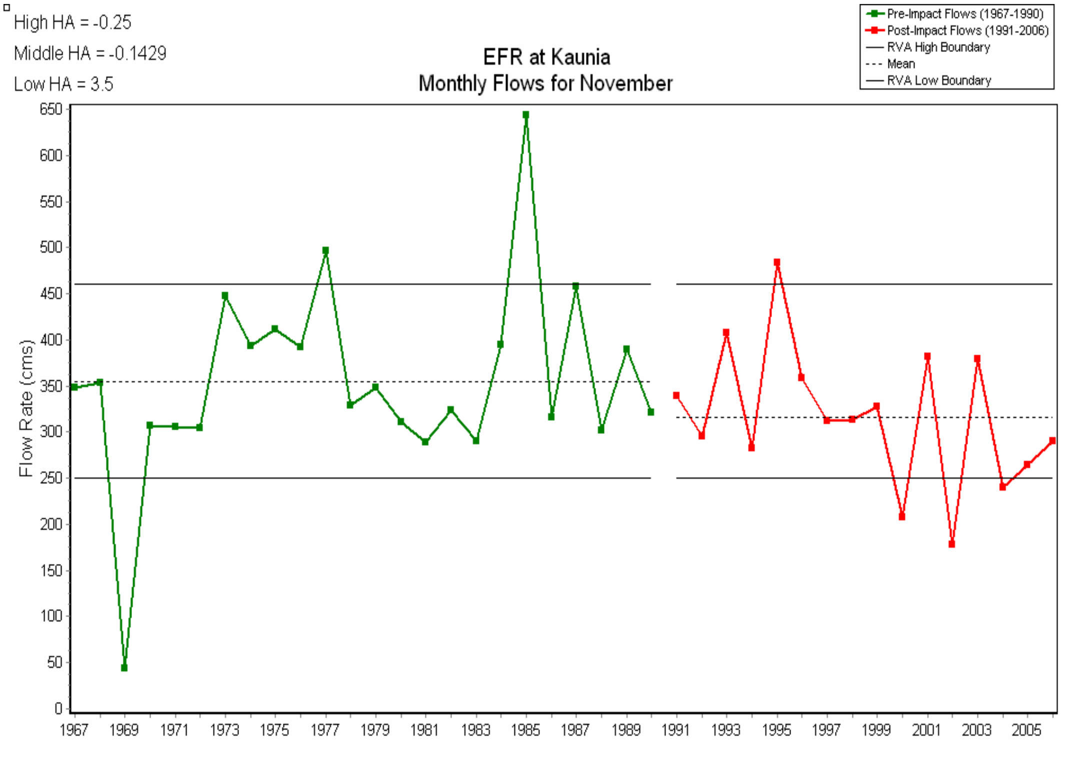


Figure D.4 Mean monthly flows with RVA targets and IHA values for the months of March to December at Kaunia of the Teesta River (Cont'd)



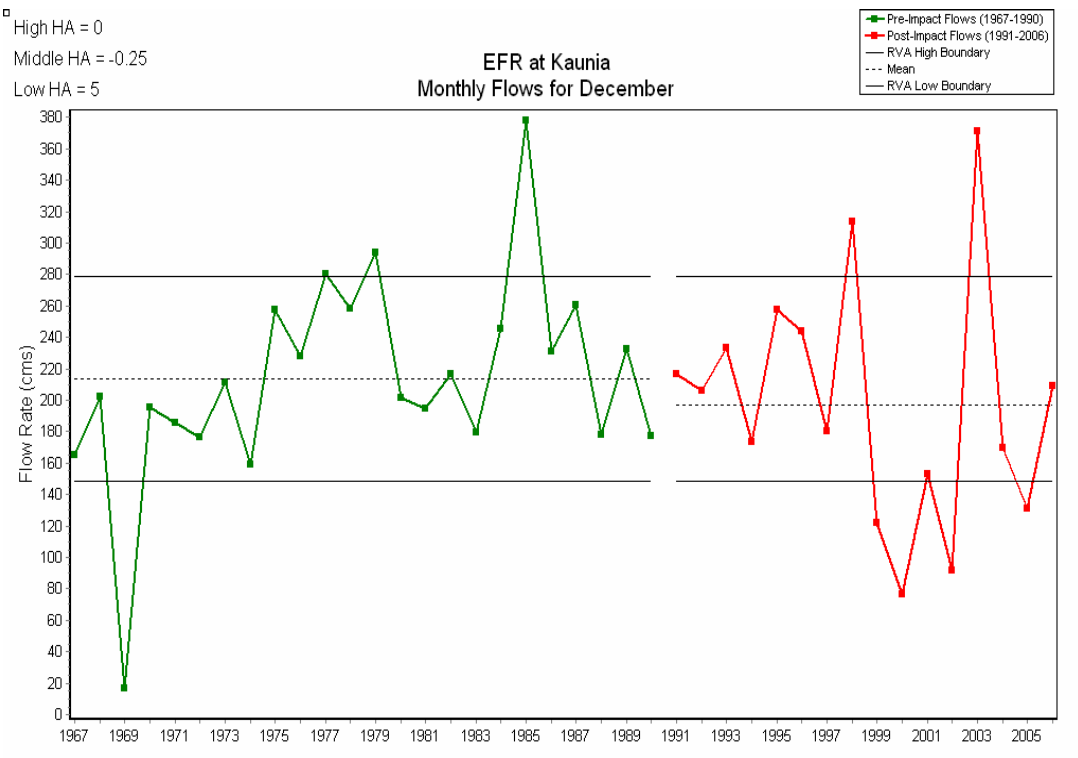


Figure D.4 Mean monthly flows with RVA targets and IHA values for the months of March to December at Kaunia of the Teesta River (Cont'd)

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Appendix E. Input to Aquarius model for Teesta River study site

The developed quadratic total benefit (TB) function for irrigation water use in the Teesta is given in Equation 5-6(c), where the unit of TB is million US$ and flow is in m^3/s. However, for Aquarius compatibility the TB needs to be converted into US$ and flow into MCM/month. With the necessary conversion, the data are presented in Table E.1 and the quadratic TB function is shown in Figure E.1.

Table 1.11 Flow and respective total benefit for irrigation water use in the Teesta site

Flow		TB ($/month)
m^3/s	MCM/m	
135.79	352	8260000
122.21	317	7420000
108.63	282	6510000
95.05	246	5540000
81.47	211	4480000
67.90	176	3330000

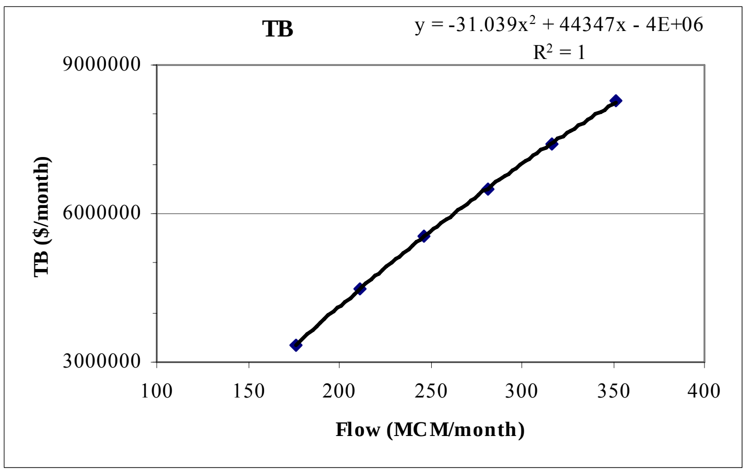

Figure 1.5 Total benefit function for irrigation water use in Teesta site

From the above shown TB function in Figure E.1, the estimated MB function is linear ($MB = -62.078*x+44347$), which needs to be converted into exponential function ($y = ae^{-x/b}$) to use in Aquarius. Here x is flow.

The linear and fitted exponential MB function is shown in Figure E.2. In this fitted exponential MB function, the coefficient values for a and b is used as 46,000 and 525.

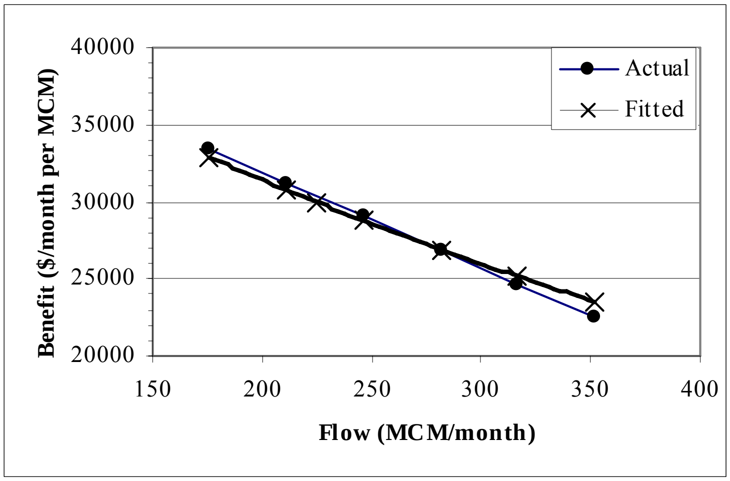

Figure 1.6 Actually developed (quadratic) and fitted exponential Marginal benefit curve

Instream water (Fisheries and navigation) benefit function is developed and given in Equations 6-8 and 6-9, where the unit of TB is US$/month and MB is US$/month per m^3/s. However, for the compatibility of the Aquarius model, the flow unit needs to be changed into MCM/month. After the necessary conversion to Equation 6-9, the obtained MB function is *MB = 481-0.63*x;* where x is flow.

From the above equation, the coefficient values of *a* and *b* are respectively 481 and 0.63 and given as input to Aquarius.

<u>Model verification</u>

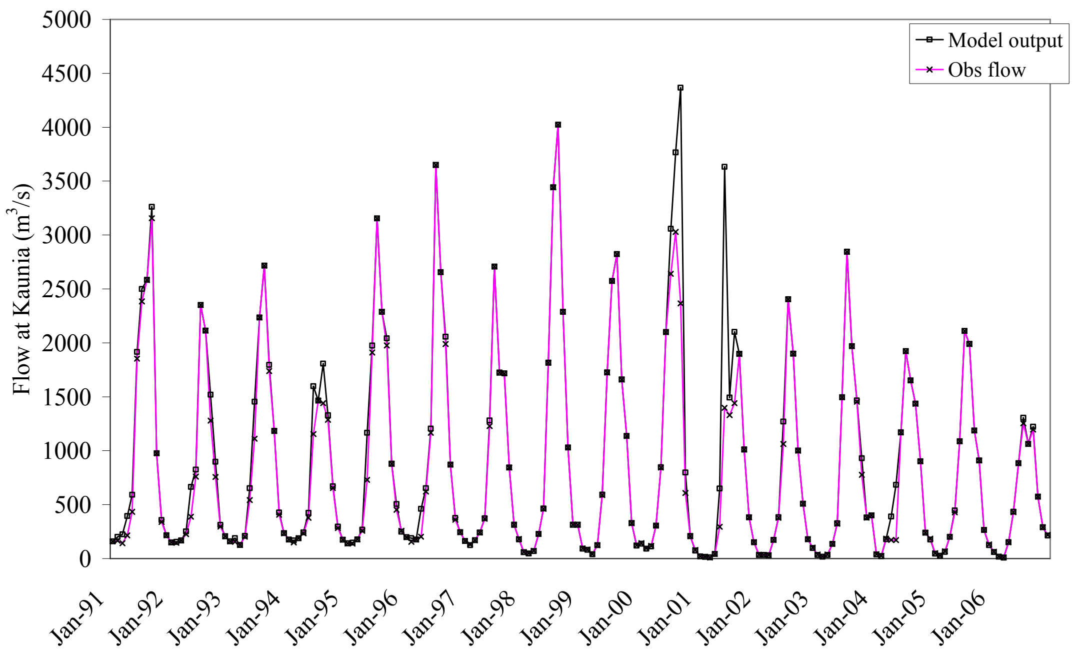

Figure 1.7 Verification of Aquarius output with observed flow at Kaunia, Teesta

Appendix F. Data and information for Konto River Basin

Table 12.1 Flow (m^3/s) from Sambong, Nogo and Nambaan river (1999 – 2008)

Year/month		Nogo River Basin	Sambong River Basin	Nambaan River Basin	Total Flow
1999	January	0.15	0.35	0.41	0.91
	February	0.15	0.34	0.40	0.88
	March	0.14	0.33	0.39	0.87
	April	0.14	0.33	0.39	0.87
	May	0.10	0.22	0.26	0.58
	June	0.09	0.21	0.24	0.54
	July	0.08	0.18	0.21	0.47
	August	0.07	0.16	0.19	0.42
	September	0.06	0.15	0.18	0.39
	October	0.08	0.18	0.21	0.46
	November	0.09	0.20	0.24	0.53
	December	0.13	0.29	0.34	0.76
2000	January	0.13	0.29	0.35	0.77
	February	0.16	0.38	0.45	0.99
	March	0.13	0.30	0.36	0.79
	April	0.12	0.28	0.33	0.73
	May	0.10	0.23	0.27	0.59
	June	0.08	0.20	0.23	0.51
	July	0.07	0.17	0.20	0.45
	August	0.07	0.15	0.18	0.40
	September	0.06	0.14	0.17	0.37
	October	0.05	0.13	0.15	0.33
	November	0.07	0.17	0.20	0.45
	December	0.05	0.12	0.14	0.30
2001	January	0.10	0.23	0.27	0.60
	February	0.12	0.28	0.32	0.72
	March	0.13	0.29	0.34	0.76
	April	0.11	0.25	0.30	0.66
	May	0.07	0.17	0.20	0.45
	June	0.08	0.19	0.22	0.49
	July	0.06	0.15	0.17	0.38
	August	0.06	0.13	0.16	0.34
	September	0.05	0.12	0.14	0.32
	October	0.07	0.16	0.18	0.41
	November	0.07	0.16	0.18	0.41
	December	0.05	0.11	0.13	0.28
2002	January	0.10	0.23	0.27	0.59
	February	0.19	0.44	0.51	1.14
	March	0.11	0.25	0.29	0.64
	April	0.09	0.20	0.24	0.52
	May	0.07	0.16	0.19	0.43
	June	0.07	0.15	0.18	0.40
	July	0.06	0.13	0.16	0.35
	August	0.05	0.12	0.14	0.31
	September	0.05	0.11	0.13	0.29
	October	0.04	0.10	0.11	0.25
	November	0.04	0.09	0.11	0.24
	December	0.04	0.10	0.12	0.27
2003	January	0.05	0.11	0.13	0.28
	February	0.08	0.19	0.23	0.50
	March	0.10	0.23	0.27	0.61

Year/month		Nogo River Basin	Sambong River Basin	Nambaan River Basin	Total Flow
	April	0.05	0.12	0.15	0.33
	May	0.05	0.11	0.13	0.28
	June	0.04	0.10	0.12	0.26
	July	0.04	0.09	0.10	0.23
	August	0.03	0.08	0.09	0.21
	September	0.03	0.07	0.09	0.19
	October	0.03	0.06	0.08	0.17
	November	0.04	0.09	0.11	0.25
	December	0.04	0.09	0.11	0.25
2004	January	0.05	0.11	0.13	0.30
	February	0.10	0.23	0.27	0.59
	March	0.11	0.26	0.31	0.69
	April	0.06	0.14	0.16	0.35
	May	0.05	0.12	0.14	0.31
	June	0.05	0.11	0.13	0.29
	July	0.04	0.10	0.11	0.25
	August	0.04	0.09	0.10	0.23
	September	0.03	0.08	0.09	0.21
	October	0.03	0.07	0.08	0.18
	November	0.03	0.07	0.08	0.19
	December	0.04	0.10	0.11	0.25
2005	January	0.03	0.07	0.09	0.19
	February	0.04	0.09	0.11	0.25
	March	0.04	0.10	0.12	0.26
	April	0.04	0.10	0.11	0.25
	May	0.03	0.07	0.08	0.17
	June	0.03	0.06	0.07	0.16
	July	0.02	0.05	0.06	0.14
	August	0.02	0.05	0.06	0.13
	September	0.02	0.04	0.05	0.12
	October	0.02	0.04	0.05	0.10
	November	0.02	0.04	0.05	0.11
	December	0.05	0.11	0.13	0.28
2006	January	0.07	0.16	0.19	0.42
	February	0.08	0.18	0.22	0.48
	March	0.07	0.16	0.19	0.42
	April	0.04	0.10	0.12	0.27
	May	0.06	0.15	0.17	0.38
	June	0.04	0.10	0.12	0.25
	July	0.04	0.09	0.10	0.22
	August	0.03	0.08	0.09	0.20
	September	0.03	0.07	0.08	0.19
	October	0.03	0.06	0.07	0.16
	November	0.02	0.06	0.07	0.15
	December	0.04	0.09	0.11	0.24
2007	January	0.02	0.06	0.07	0.14
	February	0.06	0.14	0.17	0.37
	March	0.07	0.16	0.19	0.42
	April	0.07	0.16	0.18	0.41
	May	0.04	0.09	0.11	0.24
	June	0.04	0.09	0.10	0.22
	July	0.03	0.07	0.09	0.20
	August	0.03	0.07	0.08	0.18
	September	0.03	0.06	0.07	0.16

Year/month		Nogo River Basin	Sambong River Basin	Nambaan River Basin	Total Flow
	October	0.03	0.06	0.07	0.16
	November	0.04	0.09	0.10	0.23
	December	0.07	0.17	0.20	0.43
2008	January	0.08	0.18	0.21	0.47
	February	0.12	0.27	0.32	0.71
	March	0.15	0.34	0.40	0.90
	April	0.08	0.20	0.23	0.51
	May	0.07	0.16	0.19	0.43
	June	0.06	0.15	0.18	0.39
	July	0.06	0.13	0.15	0.34
	August	0.05	0.12	0.14	0.30
	September	0.05	0.11	0.13	0.28
	October	0.04	0.10	0.12	0.26
	November	0.05	0.11	0.13	0.30
	December	0.06	0.13	0.16	0.35

Table 1.2 Observed mean monthly flow (m^3/s) in Konto that meets with Brantas (2004 – 2008)

Year	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Annual Avg
2004	7.3	10.3	13.5	11.7	7.7	8.9	7.9	7.5	9.1	9.7	9.4	13.1	9.68
2005	9.07	6.88	4.8	9.36	6.23	7.93	8.73	9	9	10.8	9.19	8.74	8.31
2006	11.4	13.44	10.25	11.28	11.72	9.38	7.96	7.2	7.09	8.59	9.85	7.65	9.65
2007	7.26	8.71	9.43	13.55	12.57	9.25	8	8	8.04	8.92	10.6	9.69	9.50
2008	13.2	16.6	21.2	14.3	12	10.9	9.1	9	9.7	12.1	12	10.7	12.57
Monthly Avg	9.65	11.19	11.84	12.04	10.04	9.27	8.34	8.14	8.59	10.02	10.21	9.98	9.94

Table 1.3 NRECA model estimated Konto flow (m^3/s) that meets with Brantas (2004 – 2008)

Year	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Annual Avg
2004	11.25	24.66	31.98	16.70	11.42	11.33	9.25	8.32	8.55	8.14	7.52	12.85	13.50
2005	11.66	15.75	17.31	19.33	10.66	12.08	9.14	8.45	7.86	8.54	9.38	26.89	13.09
2006	22.54	27.39	21.16	15.64	20.66	12.22	10.14	9.13	8.49	8.07	8.54	12.01	14.67
2007	6.96	18.35	21.39	24.70	10.94	11.30	9.05	8.15	7.64	8.39	13.65	23.76	13.69
2008	28.06	41.91	52.32	29.06	23.36	19.50	16.14	14.61	14.39	15.64	17.96	19.36	24.36
Monthly Avg	16.09	25.61	28.83	21.08	15.41	13.29	10.74	9.73	9.39	9.76	11.41	18.97	15.86

Table 1.4 Selerejo Dam - Storage-Area-Elevation Relation

Elevation (m)	Storage (m^3)	Area (m^2)
591.5	6,000.48	683,549.31
592	17,384.13	692,882.17
592.5	33,658.10	703,116.34
593	55,221.23	714,044.37
593.5	482,490.02	725,944.74
594	615,898.76	738,609.83
594.5	755,899.49	752,318.41
595	902,962.11	766,863.11
595.5	1,057,574.38	782,522.69
596	1,220,241.97	799,090.18
596.5	1,391,488.51	816,844.29
597	1,571,855.62	835,578.20
597.5	1,761,902.97	855,571.02
598	1,962,208.29	876,615.89
598.5	2,173,367.44	898,992.16
599	2,395,994.45	922,493.13
599.5	2,630,721.53	947,398.34
600	2,878,199.17	973,501.13
600.5	3,139,096.10	1,001,081.40
601	3,414,099.41	1,029,932.54
601.5	3,703,914.54	1,060,334.63
602	4,009,265.37	1,092,081.17
602.5	4,330,894.19	1,125,452.50
603	4,669,561.80	1,160,242.33
603.5	5,026,047.55	1,196,730.93
604	5,401,149.34	1,234,712.50
604.5	5,795,683.70	1,274,467.17
605	6,210,485.81	1,315,789.53
605.5	6,646,409.57	1,358,959.74
606	7,104,327.59	1,403,772.55
606.5	7,585,131.29	1,450,508.47
607	8,089,730.89	1,498,962.24
607.5	8,619,055.50	1,549,414.52
608	9,174,053.10	1,601,660.29
608.5	9,755,690.67	1,655,980.46
609	10,364,954.13	1,712,169.95
609.5	11,002,848.45	1,770,510.04
610	11,670,397.68	1,830,795.62
610.5	12,368,644.97	1,893,308.47
611	13,098,652.63	1,957,843.19
611.5	13,861,502.18	2,024,682.19
612	14,658,294.34	2,093,619.81
612.5	15,490,149.15	2,164,938.99
613	16,358,205.95	2,238,433.91
613.5	17,263,623.43	2,314,387.96
614	18,207,579.72	2,392,595.33
614.5	19,191,272.36	2,473,339.59
615	20,215,918.39	2,556,415.12
615.5	21,282,754.37	2,642,105.71
616	22,393,036.44	2,730,205.75
616.5	23,548,040.33	2,820,999.30
617	24,749,061.46	2,914,280.97
617.5	25,997,414.89	3,010,334.85
618	27,294,435.47	3,108,955.83
618.5	28,641,477.77	3,210,428.13
619	30,039,916.22	3,314,546.78
619.5	31,491,145.09	3,421,596.14
620	32,996,578.55	3,531,371.55
620.5	34,557,650.71	3,644,157.36
621	36,175,815.67	3,759,749.14
621.5	37,852,547.55	3,878,431.46
622	39,589,340.54	4,000,000.00
622.5	41,387,708.93	4,124,739.49
623	43,249,187.15	4,252,445.80

Source: PJT-I, 2007

Table 1.5 Monthly power production (MWh) from three hydropower plants

Year	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Total
Selorejo Hydropower plant													
1999	1,839	1,766	2,558	2,097	1,842	2,469	2,342	2,555	2,028	1,380	1,551	761	23,188
2000	1,758	2,869	3,272	2,637	2,458	2,303	2,262	2,001	1,623	1,694	1,442	1,038	25,357
2001	2,501	2,467	2,516	2,051	2,489	1,808	1,712	1,827	1,694	1,675	1,396	2,043	24,179
2002	1,731	2,349	2,777	3,178	2,534	2,137	1,877	1,844	2,030	2,712	2,307	1,579	27,055
2003	2,067	2,945	3,287	3,177	2,619	2,201	1,896	1,885	1,770	316	2,199	1,842	26,204
2004	2,469	2,971	3,111	3,171	2,672	1,963	1,879	1,896	1,761	1,445	2,195	1,305	26,838
2005	1,510	2,182	2,355	2,791	2,320	2,217	1,945	1,839	1,742	2,047	1,990	1,815	24,753
2006	1,530	1,758	2,468	2,366	1,898	1,757	1,808	1,732	1,363	1,720	2,169	1,983	22,552
2007	2,020	2,332	2,281	2,180	1,919	1,816	1,737	1,693	1,471	1,136	969	462	20,016
2008	452	266	1,622	2,311	1,733	2,019	2,132	2,011	1,628	1,342	2,235	1,501	19,252
Avg	1,788	2,191	2,625	2,596	2,248	2,069	1,959	1,928	1,711	1,547	1,845	1,433	23,939
Mendalan hydropower plant													
2003	7,120	5,818	7,768	5,719	5,701	6,157	5,922	6,878	6,578	6,995	8,674	6,089	79,419
2004	6,140	6,570	7,082	6,448	6,099	6,681	6,608	6,565	6,600	6,800	6,367	6,667	78,627
2005	6,511	5,083	4,982	6,741	4,924	6,129	6,628	6,449	6,272	6,789	6,265	6,921	73,694
2006	7,226	6,541	7,149	6,870	6,855	6,156	6,138	6,269	6,224	6,890	6,778	6,584	79,680
2007	6,126	5,945	6,701	6,512	5,545	6,315	6,223	6,320	6,020	6,401	6,193	6,446	74,747
2008	6,392	5,923	6,482	6,222	6,312	6,291	6,438	6,487	6,293	6,073	6,092	6,113	75,118
Avg	6,586	5,980	6,694	6,419	5,906	6,288	6,326	6,495	6,331	6,658	6,728	6,470	76,881
Siman hydropower plant													
2003	5,581	4,641	6,288	4,339	4,318	4,823	4,240	4,514	4,514	4,536	4,972	4,342	57,108
2004	4,451	4,474	5,713	5,435	4,530	4,765	4,449	4,513	4,652	5,214	4,504	4,856	57,556
2005	4,765	3,831	4,028	4,994	3,705	4,580	4,892	4,778	4,540	5,095	4,656	5,108	54,972
2006	5,679	5,275	5,474	5,631	5,615	4,628	4,598	4,600	4,473	4,698	4,533	3,877	59,081
2007	4,295	4,164	4,583	4,003	3,834	3,271	4,201	4,170	2,655	4,399	4,517	4,654	48,746
2008	3,151	4,400	4,865	4,893	4,964	4,599	4,831	4,781	4,556	4,875	5,028	5,467	56,410
Avg	4,654	4,464	5,159	4,883	4,494	4,444	4,535	4,559	4,232	4,803	4,702	4,717	55,646

Table 1.6 Estimation of original flow of Konto river

Month	Inflow to Selorejo (m^3/s)	Flow at Mendalan dam after abstraction to Siman pond (m^3/s)	Konto flow before Brantas (Observed) (m^3/s)	Local flow of Konto d/s to Selorejo (m^3/s)	Original flow in Konto (m^3/s)
1	2	3	4	5	6
Jan-04	9.66	0.00	7.3	7.30	17.66
Feb-04	15.82	2.37	10.3	7.93	24.45
Mar-04	17.91	5.67	13.5	7.83	26.44
Apr-04	11.35	3.60	11.7	8.10	20.15
May-04	9.94	0.00	7.7	7.70	18.34
Jun-04	7.27	0.71	8.9	8.19	16.16
Jul-04	6.62	0.00	7.9	7.90	15.22
Aug-04	5.54	0.00	7.5	7.50	13.74
Sep-04	6.79	0.81	9.1	8.29	15.78
Oct-04	6.16	1.40	9.7	8.30	15.16
Nov-04	8.85	1.11	9.4	8.29	17.84
Dec-04	13.78	4.82	13.1	8.28	22.76
Jan-05	9.68	0.00	9.07	9.07	19.45
Feb-05	8.73	0.00	6.88	6.88	16.31
Mar-05	10.42	0.00	4.8	4.80	15.92

Month	Inflow to Selorejo (m^3/s)	Flow at Mendalan dam after abstraction to Siman pond (m^3/s)	Konto flow before Brantas (Observed) (m^3/s)	Local flow of Konto d/s to Selorejo (m^3/s)	Original flow in Konto (m^3/s)
Apr-05	12.25	1.65	9.36	7.71	20.66
May-05	7.73	0.00	6.23	6.23	14.66
Jun-05	6.87	0.00	7.93	7.93	15.50
Jul-05	7.00	0.00	8.73	8.73	16.43
Aug-05	6.10	0.23	9	8.77	15.57
Sep-05	6.16	0.22	9	8.78	15.64
Oct-05	6.73	1.88	10.8	8.92	16.35
Nov-05	7.14	0.55	9.19	8.64	16.48
Dec-05	11.05	0.89	8.74	7.85	19.60
Jan-06	14.35	3.61	11.4	7.79	22.84
Feb-06	14.09	5.16	13.44	8.28	23.07
Mar-06	13.15	1.97	10.25	8.28	22.13
Apr-06	12.79	3.12	11.28	8.16	21.65
May-06	12.00	3.03	11.72	8.69	21.39
Jun-06	8.29	0.58	9.38	8.80	17.79
Jul-06	6.36	0.00	7.96	7.96	15.02
Aug-06	5.74	0.00	7.2	7.20	13.64
Sep-06	5.42	0.00	7.09	7.09	13.21
Oct-06	6.37	0.67	8.59	7.92	14.99
Nov-06	6.96	1.67	9.85	8.18	15.84
Dec-06	9.47	0.00	7.65	7.65	17.82
Jan-07	6.93	0.00	7.26	7.26	14.89
Feb-07	13.52	0.68	8.71	8.03	22.25
Mar-07	14.35	1.57	9.43	7.86	22.91
Apr-07	13.93	5.79	13.55	7.76	22.39
May-07	8.99	0.00	12.57	12.57	22.26
Jun-07	8.23	1.13	9.25	8.12	17.05
Jul-07	7.10	0.19	8	7.81	15.61
Aug-07	6.56	0.18	8	7.82	15.08
Sep-07	6.18	0.23	8.04	7.81	14.69
Oct-07	7.55	0.91	8.92	8.01	16.26
Nov-07	9.51	2.40	10.6	8.20	18.41
Dec-07	17.07	2.42	9.69	7.27	25.04
Jan-08	13.70	5.97	13.2	7.23	21.63
Feb-08	19.00	7.73	16.6	8.87	28.57
Mar-08	21.25	11.02	21.2	10.18	32.13
Apr-08	15.69	6.01	14.3	8.29	24.68
May-08	12.68	3.94	12	8.06	21.44
Jun-08	9.73	2.22	10.9	8.68	19.11
Jul-08	8.42	1.09	9.1	8.01	17.13
Aug-08	8.13	1.06	9	7.94	16.77
Sep-08	8.02	1.79	9.7	7.91	16.63
Oct-08	8.62	3.67	12.1	8.43	17.75
Nov-08	9.81	3.95	12	8.05	18.56
Dec-08	10.94	2.82	10.7	7.88	19.52
			MAF		18.77

Note: Columns 2 and 4 are obtained data from PJT-I, column 3 is simulated and taken from Triweko et al. (2010), column 5 = Column 4 – Column 3; Column 6 = column 2 + Column 5 + 0.7, where 0.7 m3/s is the M&I use

Appendix G. Valuation of water in Konto River Basin

Table 1.7 Crop Budget analysis for the Konto Study Site

Agriculture production Input (unit)		Labor man.d/ha	Tractor unit	Seed require-ment kg/ha	*seed unit price IDR/kg*	Fertilizer kg/ha	Equipment unit	NPK kg/ha	Pesticide kg/ha	Land rent unit	Total input cost (10^9 IDR)	Per hectare input cost (IDR/ha)	Per hectare input cost (US$/ha)
Agriculture production Input unit price (IDR)		28,200	300,000			4,900	25,000	4,750	25,000	3,700,000			
Crops	Area irrig-ated (ha)	Input requirements for the crops (*except seed unit price column*)											
Paddy Dry-1	11,835	50	1.25	40	5000	1	44	350	7	1	102.1	8,627,750	958
Paddy Dry-2	2,438	58	1	40	5000	1	44	350	7	1	21.4	8,778,406	975
Paddy wet	23,275	57	1.5	40	5000	1	50	350	7	1	210.6	9,050,199	1005
Polowija Dry-1	10,638	35	0.75	25	5500	0.5	30	250	5.5	0.75	65.9	6,202,195	689
Polowija Dry-2	21,336	40	0.75	25	5500	0.5	30	250	5.5	0.75	135.3	6,343,230	704
Total Cropped Area (ha)	**69,522**								Total cost (10^9IDR)		535.4		
Net Area (ha)	**30,431**								Cost (IDR/ha)		17,596,289		

Table 1.8 Crop wise and at the project level irrigation water value

Crops	Area irrigated (ha)	Potential Yield (t/ha)	Unit output price (IDR/kg)	Total output value (10^9 IDR)	Per hectare output value (IDR/ha)	Per hectare input cost (IDR/ha)	WRF (mm)	WWR (mm)	Value of diverted water (IDR/m^3)	Value of diverted water (US$/$m^3$)
Paddy Dry-1	11,835	5.4	2200	140.6	11,880,000	8,627,750	230	418	777	0.086
Paddy Dry-2	2,438	5.9	2200	31.6	12,980,000	8,778,406	1080	1,965	214	0.024
Paddy wet	23,275	5.1	2200	261.1	11,220,000	9,050,199	214	388	560	0.062
Polowija Dry-1	10,638	2.25	3500	83.8	7,875,000	6,202,195	122	222	752	0.084
Polowija Dry-2	21,336	2.25	3500	168.0	7,875,000	6,343,230	332	604	253	0.028
Total cropped area (ha)	**69,522**	Total output value (10^9 IDR)		685.2						
Net irrigated Area (ha)	**30,431**	Output value IDR/ha		22,516,046		Water value (IDR/m^3)			584	0.065

Table 1.9 Fish price at the Konto Study site

Fish type	Mas/Tombro	Tawes	Nila	Mujahir	Lele	Belut	Ikan Lain	Udang
Unit price (IDR/kg)	12,500	11,000	9,000	8,500	9,500	14,000	11,000	19,000

Table 1.10 Monthly fish production (tonne) and fishery benefit (10^6 IDR) from Selorejo Reservoir

	Year 2008											
Fish type	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Mas/Tombro	0.082	0.0765	0.065	0.065	0.065	0.065	0.065	0.065	0.065	0.1855	0.0585	0.0075
Tawes	0.5	0.6125	0.5375	1.725	0.425	0.325	0.325	0.325	0.3	0.25	0.25	0.2475
Nila	3.9825	4.147	1.3375	2.0125	0.5	0.5	9.5	2.2	0.45	3.244	4.589	3.85
Mujahir	0.775	1.1	1.05	1.1	1.1	1	2.525	2	0.75	0.75	0.75	3.825
Lele	0	0	0	0	0	0	0	0	0	0	0	0
Belut	0	0	0	0	0	0	0	0	0	0	0	0
Ikan Lain	0.0525	0	0.095	0.3875	0	0	0	0	0	0	0	0
Udang	0	0.0825	0	0	0	0	0	0	0	0	0	0
Total Production	5.392	6.0185	3.085	5.29	2.09	1.89	12.415	4.59	1.565	4.4295	5.6475	7.93
Benefit	49.5	55.9	28.7	51.5	19.3	17.4	111.4	41.2	14.5	40.6	51.2	70.0
	Year 2009											
Mas/Tombro	0.45	1.42	1.16	0.87	1.08	0.90	0.10	0.00	0.00	0.36	0.22	0.40
Tawes	2.74	4.46	4.16	3.44	2.10	1.80	0.00	0.00	0.00	0.00	0.00	0.89
Nila	6.99	9.82	9.96	6.62	10.27	7.53	2.68	3.00	2.15	3.77	3.85	6.20
Mujahir	2.48	3.11	3.14	2.52	2.54	1.54	0.00	0.00	0.00	1.63	1.54	2.13
Lele	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Belut	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Ikan Lain	0.59	1.53	1.50	1.17	0.32	0.72	0.00	0.00	0.00	1.57	0.79	0.93
Udang	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	1.31	1.08	1.14
Total production	13.23	20.34	19.92	14.62	16.30	12.48	2.78	3.00	2.15	8.63	7.47	11.67
Benefit	126.0	198.4	193.0	142.5	154.0	119.7	25.4	27.0	19.4	94.3	79.6	120.3

	Year 2010											
Mas/Tombro	0.53	0.59	0.49	0.63	0.64	0.22	0.39	0.35	0.35	0.38	0.41	0.64
Tawes	2.65	2.90	2.67	2.12	2.11	1.68	0.83	1.01	1.22	1.32	1.19	0.00
Nila	6.89	7.21	6.29	8.14	8.15	6.32	7.16	6.50	7.32	7.41	7.59	8.84
Mujahir	2.21	2.70	2.34	2.89	2.98	2.50	1.79	1.76	1.80	1.85	1.99	3.23
Lele	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Belut	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Ikan Lain	0.66	0.57	0.53	0.64	0.50	0.10	0.69	0.63	0.38	0.35	0.77	0.64
Udang	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Total production	12.93	13.97	12.31	14.41	14.36	10.81	10.86	10.23	11.06	11.31	11.94	13.35
Benefit	123.7	133.3	117.7	135.9	135.2	100.4	101.3	95.6	103.0	105.5	111.8	122.0
Avg Monthly production	10.52	13.44	11.77	11.44	10.92	8.39	8.69	5.94	4.93	8.12	8.35	10.98
Avg. Monthly fishery benefit	99.7	129.2	113.1	110.0	102.8	79.1	79.3	54.6	45.6	80.2	80.9	104.1
Avg benefit (10^3 \$)	11.08	14.35	12.56	12.21	11.42	8.79	8.81	6.06	5.07	8.90	8.98	11.56

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Appendix H. Input to Aquarius model for Konto River Basin

Table 1.11 Physical data set for Selorejo reservoir as input in Aquarius

Parameter	Parameter value	Remark
Elevation vs storage function	Coefficient values c1=596.87; d1=0.0094	Elevation vs storage relationship is established based on the data provided in Table E.1 and as established in Figure G.1.
Area vs storage function	Coefficient values c2=0.8468; d2=0.3414	Area vs storage relationship is established based on the data provided in Table E.1 and as established in Figure G.2
Initial and final storage	14.5 MCM	
Minimum storage	8.09 MCM	Based on lowest operating level for hydropower
Maximum storage	39.6 MCM	Based on maximum operating capacity of the reservoir

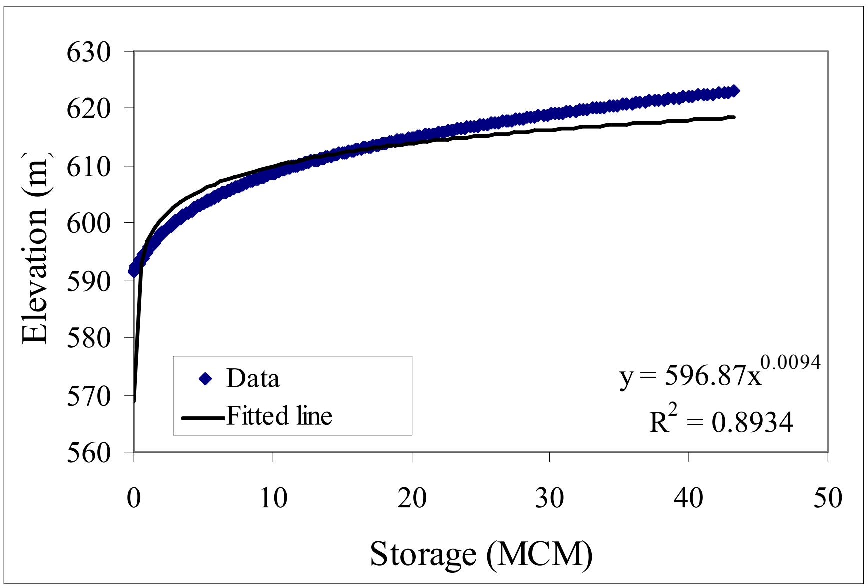

Figure 1.1 Elevation vs Storage relationship for Selorejo reservoir

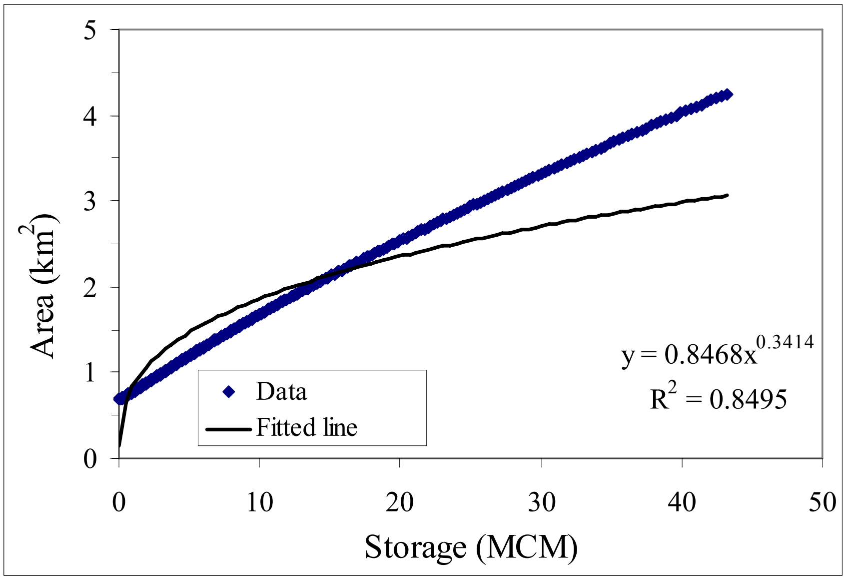

Figure 1.2 Area vs Storage relationship for Selorejo reservoir

Table 1.12 Input data for Hydropower to Aquarius model for Konto

Parameter	Hydropower plant			
	Selorejo	Mendalan	Siman	Remark
Installed capacity	4.5 MW	7 MW	9.9 MW	As obtained from PJT-I
Design Discharge	14.8 m^3/s	8.5m^3/s	8.5 m^3/s	As obtained from PJT-I
Efficiency	0.83	0.73	0.74	As mentioned in Section 10.1
Energy rate vs Storage	a1=53.4 b1=0.97766	a1=298.9 b1=0.000	a1=211.6 b1=0.000	First *erf* is calculated based on Equations 3-3 & 3-4. Then *erf* vs storage is plotted in Figure G.3

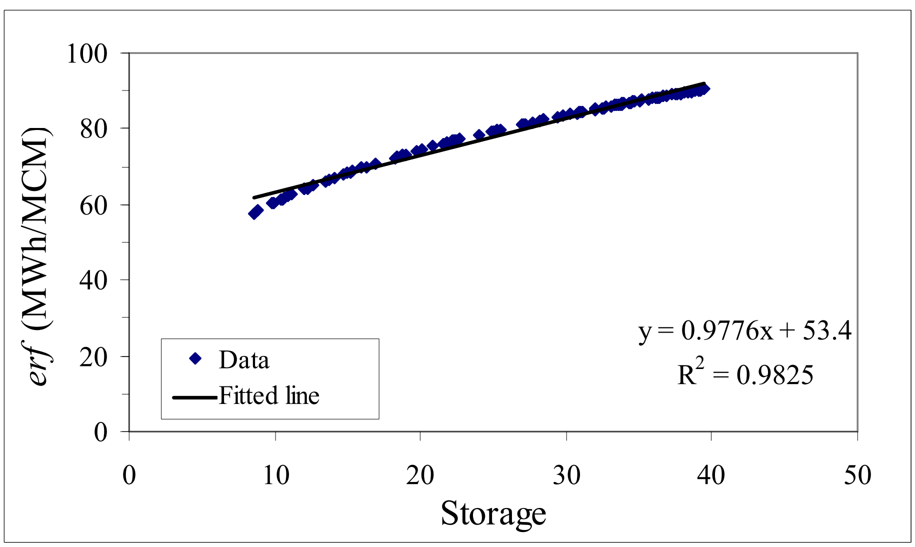

Figure 1.3 Energy rate vs storage function for Selorejo power plant

The developed quadratic total benefit (TB) function for irrigation water use in the Konto is given in Equation 10-1, where the unit of TB is million US$ and flow is in m^3/s. However, for Aquarius compatibility the TB needs to be converted into US$ and flow into MCM/month. With the necessary conversion, the data are presented in Table H.3 and the quadratic TB function is shown in Figure H.4.

Table 1.13 Flow and respective total benefit for irrigation water use in the Teesta site

Flow		TB ($/month)
m^3/s	MCM/m	
16.51	42.79	2770926
14.86	38.51	2475716
13.21	34.23	2184167
11.56	29.95	1886826
9.90	25.67	1582687
8.25	21.39	1270515

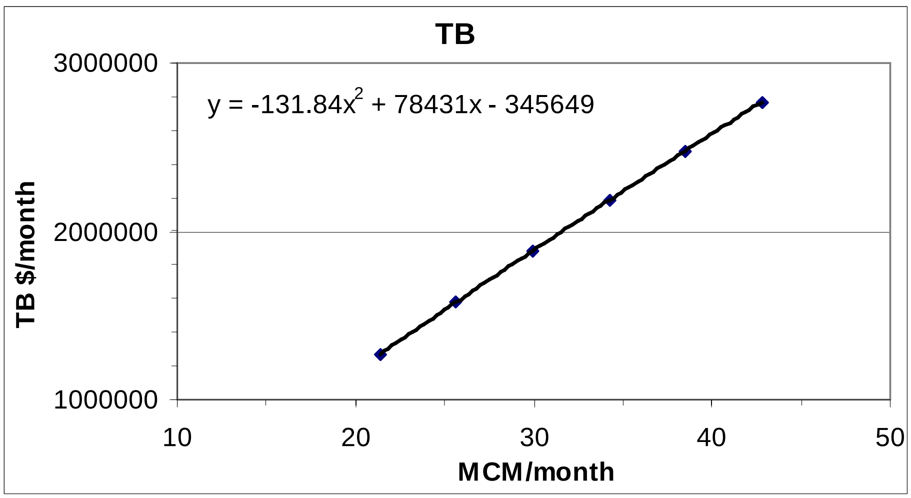

Figure 1.4 Total benefit function for irrigation water use in Konto river basin

From the above shown TB function in Figure H.4, the estimated MB function is linear ($MB = -263.68*x+78431$), which needs to be converted into exponential function ($y = ae^{-x/b}$) to use in Aquarius. Here x is flow.

The linear and fitted exponential MB function is shown in Figure H.5. In this fitted exponential MB function, the coefficient values for a and b is used as 78,900 and 265.

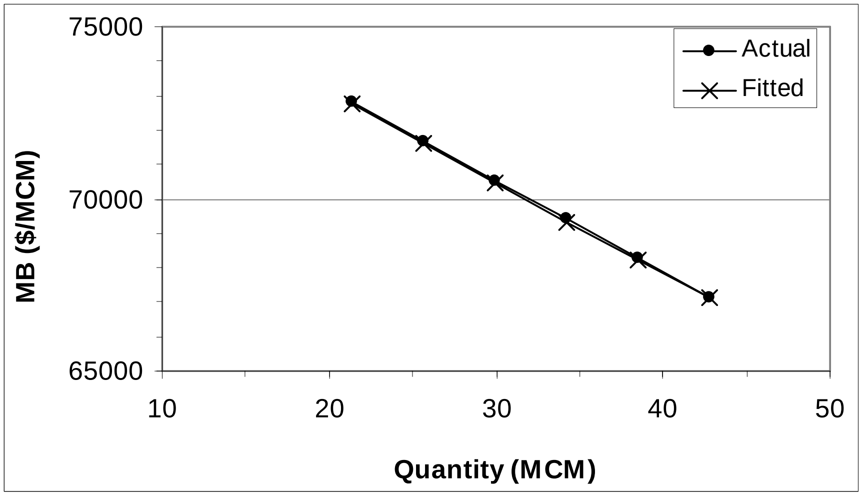

Figure 1.5 Actually developed (quadratic) and fitted exponential Marginal benefit curve